COMPUTER SIMULATIONS OF SHEEP GRAZING
IN
THE ARID ZONE

by

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COMPUTER SIMULATIONS OF SHEEP GRAZING IN THE ARID ZONE

SUMMARY

This thesis describes a computer simulation model of Wertigo paddock near Whyalla, South Australia. Wertigo is a 2200 ha, arid chenopod shrubland paddock grazed by approximately 300 merino sheep under a set stocking management policy.

The thesis emphasises a review and comparison of submodels applicable to arid or semi-arid zone grazing systems, but includes original field work and data analysis where necessary. Several published models of non-specific arid zone sites were taken as a basis for this project. The detail with which the spatial variability of the grazing processes are simulated, distinguishes this model from most published grazing models. The paddock model includes 37 cells (point models) and simulates the hourly movement and behaviour of up to 10 flocks within them.

The paddock model includes 5 major submodels; climate, plant growth, sheep behaviour, consumption, and physiology. The climate submodel includes a Markovian daily rainfall generator, a stochastic diurnal and annual temperature cycle model, a short and long wave radiation model and a soil moisture model. The plant growth model is based on an analysis of the Koonamore Vegetation Reserve photographic records from 1926 to 1972, and includes two perennial and two ephemeral taxa. The sheep behaviour submodel describes the hourly movement of sheep flocks around the paddock. It includes sheep heat and water balance models as the major determinants of flock behaviour. The sheep consumption model is based on grazing experiments carried out near Wertigo, and treats sheep grazing as a predator-prey situation.

No attempt is made to follow energy, or any particular element, throughout the model, although in various parts, water, plant organic matter, nitrogen and energy flows are simulated. Separate validation of each submodel has been attempted. No data of sufficient detail were available to validate the paddock model as a whole, but the output agrees with our present understanding of the system in all important aspects.

A series of management experiments emphasising the spatial aspects of the model are described and discussed. They showed that the system is very sensitive to small changes in the amount of rainfall, and that the effect of normal size flocks is relatively small except in the vicinity of the water-point.

DECLARATION

This thesis contains no material which has been accepted for the award of any other degree or diploma in any University. To the best of my knowledge and belief this thesis contains no material previously published or written by another person, except where due reference is made in the text.

Ian R. Noble.

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A DESCRIPTION OF THE STUDY AREA

1.0 *Introduction*

The aim of this project, stated in the title of the thesis, was to produce computer simulation models of sheep grazing arid zone paddocks. The reasons for attempting such a project, and a more detailed discussion of its development, are included in chapters 3 and 4. Prior to this, the two fields of science brought together in the project, namely arid zone ecology and computer simulation, are briefly reviewed.

This chapter describes the history, geography and management of the area shown in the maps in figure 1.2. This is the area studied in most detail and includes Wertigo paddock, the site of the most intensive studies to be described in the thesis. Chapter 2 briefly reviews the use of simulation and its application to ecology. The structure of the thesis is outlined in figure 1.1 and is described more fully in section 4.6.

1.1 *History*

The arid and semi-arid lands throughout the world have proved to be very unstable, especially under the impact of man and his grazing animals. The history of these changes has been well documented in the UNESCO publication edited by Stamp (1961).

The Australian arid lands have been subject to domestic grazing animals for a much shorter time than most other arid areas, however several classic examples of mis-management have occurred. Meinig (1962) described the spread of wheat cultivation in South Australia during the 1870's and 1880's. Semi-arid lands were cropped and good returns for a few years encouraged further expansion which was only halted by the drought of 1880-82. The sheep industry also shows a classic case of overestimation of the potential carrying capacity followed by a decline in sheep numbers (Davidson, 1938, cited as a text book example by Odum, 1971).

The Whyalla area was settled later than most of the southern arid areas due to a lack of surface water. The first grazing leases were not taken up until 1857 (Lincoln Gap, 50 km north of Whyalla); the first lease including what is now Middleback station, Wertigo paddock and the Whyalla township site was taken up in 1868 (Richardson, 1925). Wool production has always been the main source of income from these lands.

The Roopena properties came into the ownership of the Nicolson family early this century. Wertigo paddock is near the Middleback station homestead, and until recently was managed from there. In 1971 it was transferred to Nonowie station, another of the Roopena properties.

1.2 *Vegetation*

This thesis deals mainly with the low shrubland formation (terminology as in Specht, 1972), otherwise known as shrub steppe. This formation is common in southern Australia and is usually dominated by semi-succulent, chenopod shrubs less than 2 m tall. The understory consists of ephemeral and short lived perennial grasses and forbs.

Most of the shrubs are palatable to stock but in some areas (e.g. the Riverine Plain) the shrub layer has been destroyed and replaced by a more productive disclimax perennial grassland (Moore, 1970). In most of South Australia transition to disclimax grasses is unsuccessful since the replacement grasses tend to be too ephemeral, however some graziers do attempt to 'thin out' the bush with the subsequent loss of reserve feed and risk of erosion. The approach to modelling such a perennial shrub-ephemeral understory system, will differ from the approach to communities similar to the Riverine Plain, or to the less erodable and less shrub dominated sandy soils in South Australia.

Chenopod shrub steppe is an important grazing resource in South Australia. It is also the best studied arid zone vegetation formation in the state since the three major sites of arid zone experimental work; Koonamore Station, Yudnapinna Station and the Roopena properties in the Whyalla area, (fig. 1.2) all occur in this formation. It should be noted that the Roopena area is usually described as a low woodland formation dominated by *Acacia sowdenii* (Western myall) (Specht, 1972). However the shrub layer is similar to the chenopod shrub steppe, and the actual study paddock is predominately shrub steppe.

Further details about the vegetation and soils may be found in Wood (1937), Specht (1972), and for the Whyalla area in particular in Crocker (1946) and Crocker & Skewes (1941). The Australian arid lands have been reviewed in more general terms in the book edited by Slatyer & Perry (1969). The vegetation and soils of Wertigo paddock are reviewed in more detail in section 4.1.

1.3 *Management*

The management and organization of the wool industry in Australia have been summarized in the book edited by Alexander & Williams (1973) and more particularly by, Chapman et al. (1973).

The sheep industry in South Australia is confined to south of the 'dog (i.e. dingo) proof fence'. Cattle predominate to the north of this fence, but in recent years some southern sheep lands, and especially those with good grass cover, have been grazed by cattle. All the sheep are merinos and most are of a strong wool strain developed by local studs.

Over 93% of the occupied South Australian arid land is held under 21 or 42 year lease (Heathcote, 1969) and is regulated by the Pastoral Act which sets minimum stocking rates but also obliges the leasee not to depreciate "the ordinary capacity of the land for depasturing stock". A portion of the Roopena holdings is perpetual lease.

Until the 1880's the sheep were shepherded but this was replaced by fenced paddocks and water-points based on dams or bores. The Roopena stations practise a fixed stocking policy (i.e. approximately the same number of sheep are run in a paddock at all times, and only a minimal amount of stock movement between paddocks occurs). They tend to use smaller paddocks and more water-points than surrounding stations, and this is due partially to the development, early this century, of an extensive system of piped water from a large well. Paddock sizes in the area vary from 500 ha to 5000 ha.

1.4 *Research*

South Australia has a relatively long history of arid zone research. The Botany Department, and the Waite Agricultural Research Institute (both part of the University of Adelaide) have had a major research interest in the arid zone since the 1920's. However, with two exceptions, this work has tended to be piecemeal and ad hoc, as has been most other Australian arid zone research until recently. The first exception is the Koonamore experiment which has continued since 1926. It is a study of regeneration after the cessation of heavy grazing (see section 4.5 and 6.31). The second was the Yudnapinna experiment which was a grazing trial carried out over the period 1938 to 1951 (see section 4.5).

A large amount of descriptive, vegetation and soil survey work has been reported and this is summarized in Leigh & Noble (1969), Specht (1972) and the Atlas of Australian Soils (Northcote, 1960). Most of the other arid zone research work has originated from the major research centres at Alice Springs (N.T.), Deniliquin (N.S.W.) and Charleville (Qld.) and this is reviewed, along with research from other parts of the world, in the appropriate chapters.

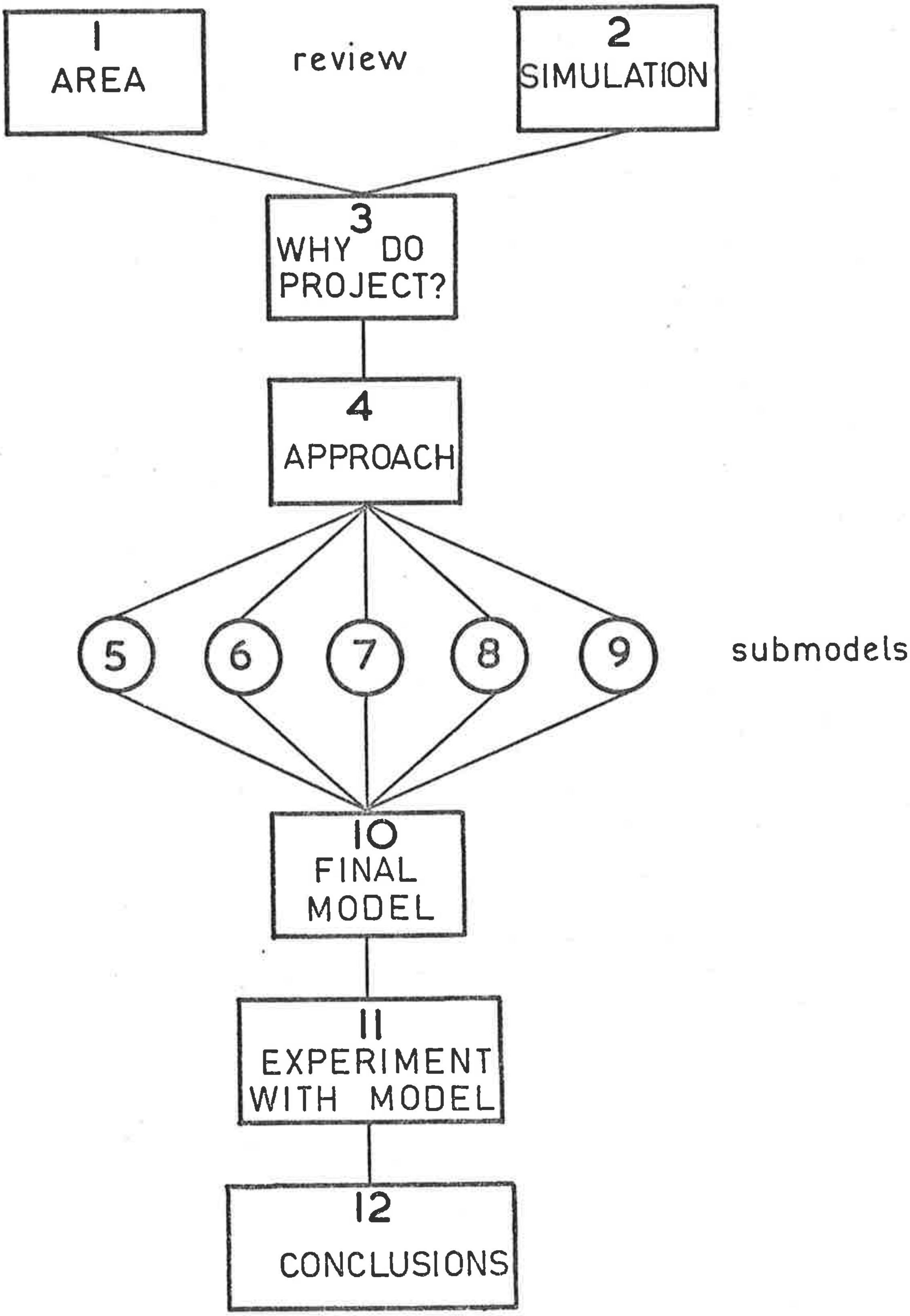


Fig. 1.1. The thesis structure and chapter topics.

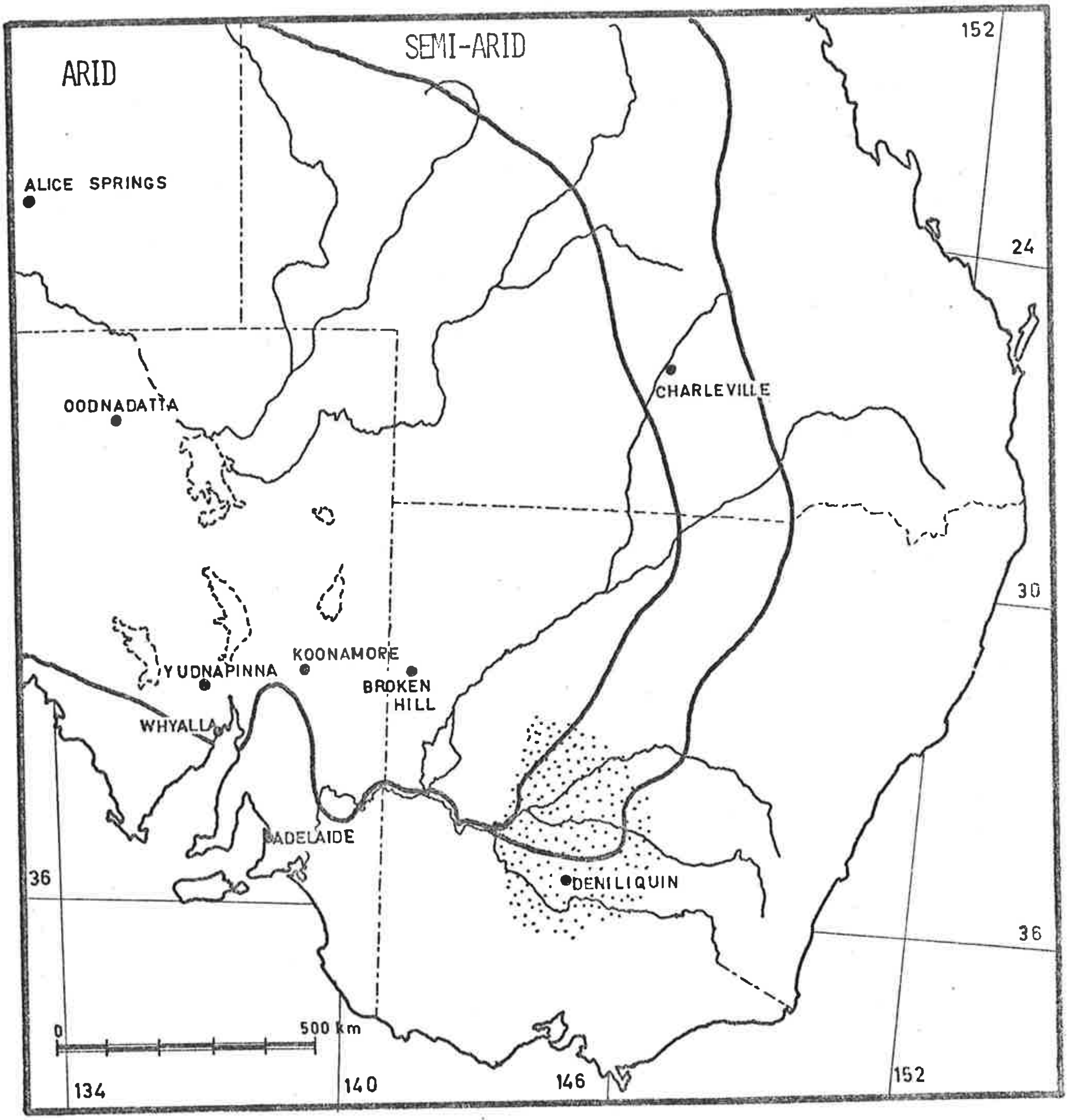


Fig. 1.2a. A locality map of the south eastern arid and semi arid areas of Australia. The stippled area is the Riverine Plain.

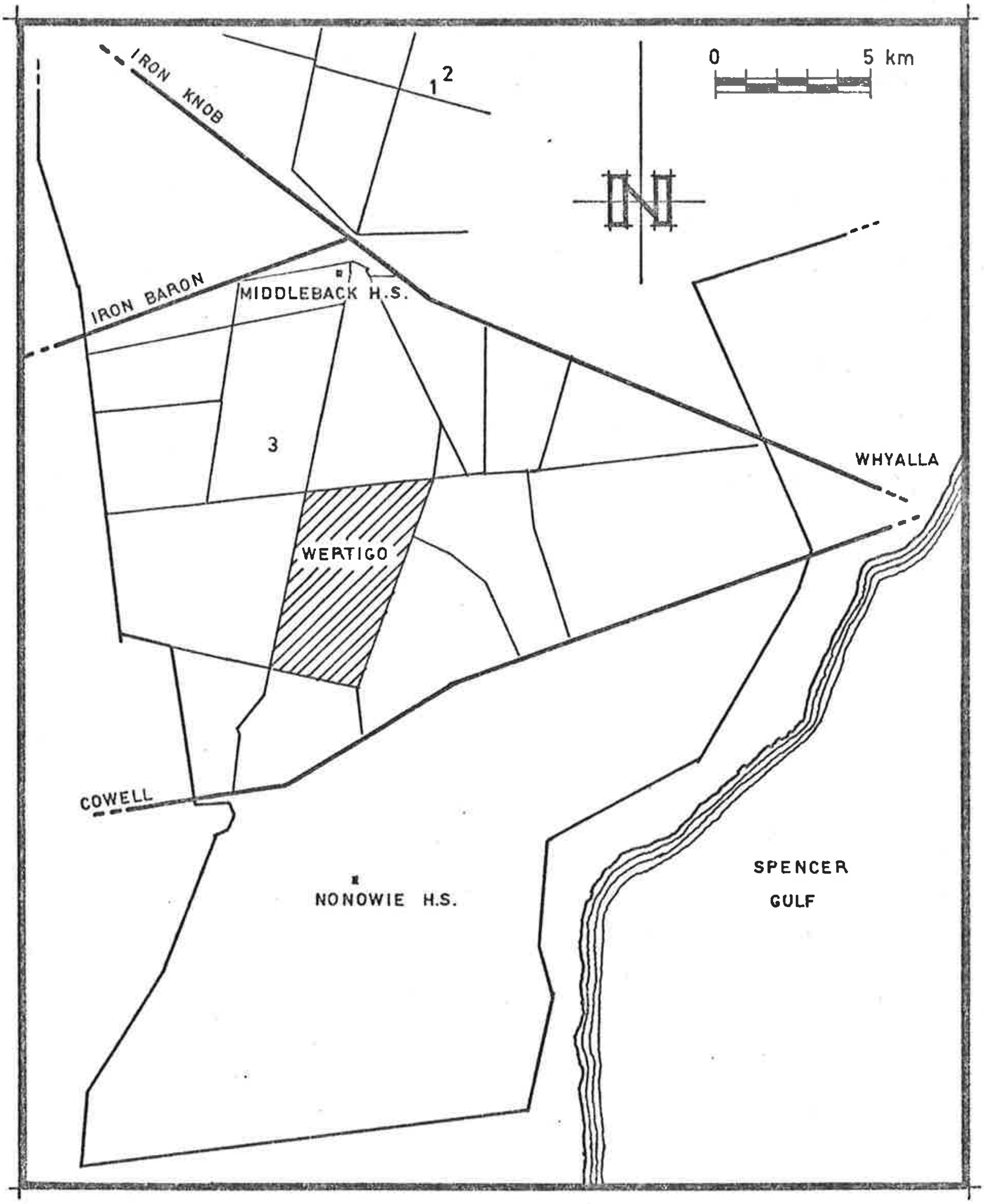


Fig. 1.2b. The southern portion of the Roopena properties showing the position of Wertigo paddock relative to other features. The digits 1, 2 & 3 indicate the sites of the November 1972, January 1973 and May 1973 grazing trials described in chapter 7.

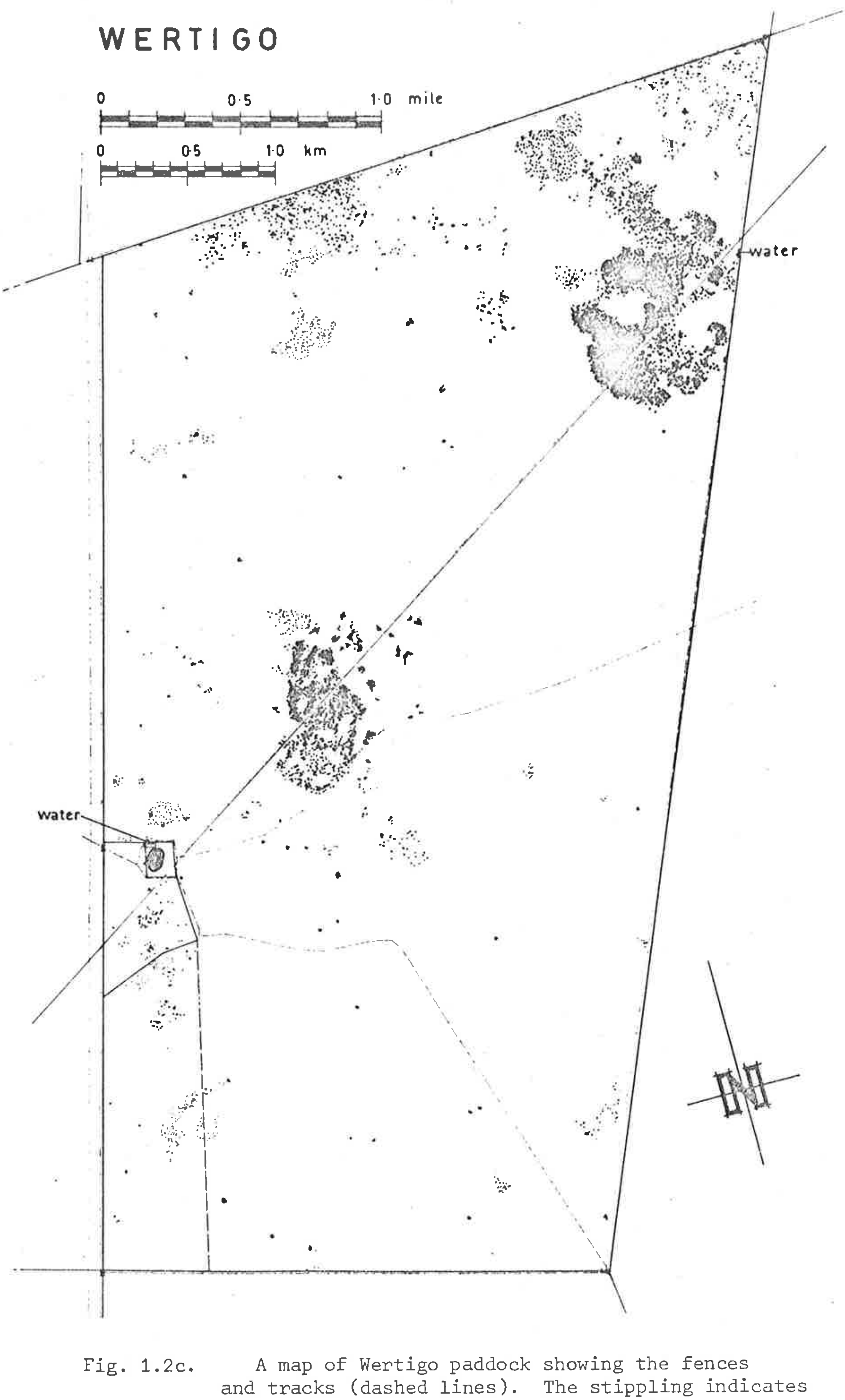


Fig. 1.2c. A map of Wertigo paddock showing the fences and tracks (dashed lines). The stippling indicates the position of trees. The diagonal line running S.W. to N.E. represents a high voltage power line and its maintenance track.

COMPUTER SIMULATION

2.0 *Introduction and definitions*

Before reviewing the field of computer simulation and its application to ecosystem modelling, it is useful to define some of the key terms. I present here, definitions of the words 'system','model' and 'simulation'. Virtually every author reviewing this field proposes new, or at least modified, definitions of these terms, each definition tending to be more 'general' than those previous. I will not attempt to review this debate, instead I merely present definitions used elsewhere which I think best describe the usage of the terms in this thesis.

Patten (1971) has defined a system as,

> "...an assemblage of objects united by some form of interaction or interdependence in such a manner as to form an entirety or whole".

The term 'objects' should be treated in a very broad sense.

A model is often defined as some form of abstraction of the real system. This is a very common definition which often leads to a discussion of reality and man's concept and models of it. To minimize philosophical problems I prefer to use the definition of Chesnut (1965) quoted in (and made more general by) Thesen (1974),

> "A model is a qualitative or quantitative representation of a process or endeavour that shows the effects of those factors which are significant for the purpose being considered".

The emphasis on the purpose of the model is important in both judging the factors to be included in the model, since the model cannot bear a 1:1 relationship to the system, and also in assessing whether the model is complete or, at least, useful.

A simulation is a method of extracting a solution from the model. The method will vary with the type of model. In this thesis, 'simulation' will usually refer to a digital computer simulation and usually to the method of extracting solutions by differential or difference equations.

2.1 *History of simulation*

It is difficult to define when a deliberate simulation was first used as a tool. Lewis (1967) described some 'scientific' modellers of the seventeenth to nineteenth centuries who used physical analogies to experiment with biological systems. However I would trace simulation back much earlier than this. One of the first simulations must be the game i-go which originated as wei-hai in China before 600 B.C. (Bell, 1960). This was, and still is, recommended as a training in tactics for military officers. It is interesting to note that many of the modern approaches to systems analysis and simulation were first developed in war gaming (Wilson, 1968).

Another example, more directly the fore-runner of computer simulation, also occurred in China. Needham (1971) pointed out that rain and snow gauges were in regular use in China before the thirteenth century A.D., and that the readings were probably conveyed to the controllers and planners of the river system down stream. Although there is no definite evidence, it is clear that there was the potential for quantitative models and even simulation in the planning process.

Analogue computers have been used for simulation of control processes since the 1930's and digital simulation began in the late 1940's (McLeod, 1968). It is difficult to distinguish what were the first ecological, computer simulations since they tended to arise out of mathematical population models. However the models of predator-prey relationships published by Holling (1965, 1966) probably gave more impetus to complex ecosystem modelling than any others.

2.2 *Basic concepts in modelling*

This field has been extensively reviewed and only a few points will be discussed here. Thesen (1974) has listed three major uses of models; (i) information storage, (ii) communication, and (iii) problem solving and design. Dale (1970) has defined the steps in modelling as the lexical phase (i.e. defining which parts of the system are of interest), the parsing phase (i.e. defining the relationships between these parts), the modelling phase (i.e. specifying how changes in the modelled system take place) and the analysis stage, in which he includes the solution of the model and subsequent analyses. Many other authors have defined similar steps. In a data-poor field such as ecosystem simulation it is common to go through this series of steps many times refining the model on each pass. The steps become a repeated process of "propose and model -- review -- modify". Goodall (1972) has discussed the steps and techniques as they apply to ecosystem modelling in more detail.

Validation is an important process in computer modelling. In this thesis I use the term validation to mean any process which increases the user's confidence that the model reflects those parts of the real world it was designed to model. Gilmour (1973) has described 'design validity', which deals with the consistency of the underlying mechanism of the model, and 'output validity', which deals only with the quality of the data produced by the model. Output validity can be assessed by various statistical tests dealing with the stability, predictive ability and sensitivity of the model (see Mihram [1972] for a more detailed discussion). In most situations the establishment of output validity is the most important part of the validation procedure. However, in data poor fields such as ecosystem simulation, design validation becomes relatively more important. The process is often subjective, and asks whether the assumptions, workings and results in general are consistent with our understanding of the system. This is essentially a form of the test described by Turing (1950) as an 'imagination game'. In this test, if a person knowledgeable with the system to be modelled cannot distinguish between the model and reality when provided with output from both, then the model is realistic. This form of test has had to be used many times in this thesis.

The term verification is used in this thesis to mean the process of checking that the model is working as it is intended, independently of its validity.

2.3 *Simulation languages*

A simulation language offers many advantages over a general higher level language such as FØRTRAN. A good simulation language will reduce the programming task since it takes care of many items itself. It provides a guide to the conceptual structure of the model which can reduce the intellectual task of defining and communicating the model. It will also allow easy modification, both for model improvement and for experimental purposes. Many languages have very useful data collection, analysis and presentation facilities.

However, there are many limitations to using a simulation language. Usually the range of languages available on a given computer is limited, and often no simulation language suitable for the task is available. The number of people fluent in the language is usually very limited making communication and transportability of the model difficult. Until recently most simulation languages tended to be either discrete or continuous and it was difficult to model discrete processes in a continuous language and <u>vice versa</u>. In recent years many of the technical problems have been overcome, but the ideal language does not yet seem to exist.

I have used FØRTRAN for all the models presented in this thesis. I chose FØRTRAN because no suitable simulation language was available and because more biologists are conversant with this language than any other.

THE PROJECT

3.0 *Introduction*

There is no doubt that we are faced with an increasing need to understand and to manage complex systems. By the definitions presented in section 2.0 this means that we need models of the systems. The models are to serve two main purposes. First, to serve as a vehicle or structure for logical thought and debate, and second to provide an aid to the management of the system. The former purpose is best exemplified in theoretical physics (e.g. the 'steady state' versus 'big bang' models of the universe), and the latter in political and sociological problems (e.g. Meadow's [1972] attempt to build a world model).

Models are needed for both purposes in the study of ecosystems, and computer simulation models appear to be particularly suitable. This case has been argued elsewhere by many authors (e.g. Van Dyne, 1969b; 1972; Goodall, 1972) and need not be repeated here.

3.1 *The project*

In 1970 I decided to build a computer simulation of an arid grazing system. This decision was a consequence of the facilities, funds and guidance available in a Botany Department and my own interests and previous experience. It was also recognised that the grazing system is a particularly suitable example for the development of computer simulation techniques. There was apparently an adequate background of research on which to base the model, and, although the literature relevant to the Australian arid zone sheep industry was smaller than that for the United States beef industry, it was better studied than most other Australian grazing industries. There had already been calls for a more holistic approach to arid ecosystems (e.g. Perry, 1966), and several other groups had started similar projects.

An important factor in the initial decision was the lead given by Goodall (1967, 1969). He published a computer simulation model of an Australian arid zone sheep paddock, "to show the potentialities of the method and to direct attention to the type of data required [rather] than to report results". Goodall emphasised that, although the available data were scanty, reasonable estimates of the parameters could be made and a realistic model produced. He also emphasised the necessity to deal with spatial heterogeneity in the model - a factor that had received little attention in ecosystem models up until then - or since.

I decided to model a single arid zone paddock since this is the natural ecological unit of the system. An arid zone paddock is small enough to be nearly homogenous with respect to the weather, but large enough to contain much heterogeneity in soils, vegetation and animal activity, all bounded within the definite boundary of the paddock fence. It may have been of more direct relevance to the wool industry to model the basic economic unit of the system, i.e. the station (c.f. Chudleigh & Filan, 1972). However, this would have required facilities and guidance which were not available. Moreover, the success of station models will depend on the accuracy, precision and efficiency of the paddock models on which they must be based. It has long been recognised that a detailed understanding of the reaction of the vegetation to grazing is needed, if sound management is to be practised. Dixon (1892) warned that already large areas of grazing country had been destroyed due to poor management. Ratcliffe (1936) was engaged by the South Australian Government to report on erosion in the arid pastoral areas. He emphasised that,

> "Permanent pastoral settlement is only possible when the stocking is in equilibrium with the vegetation, and not merely exploiting the plant capital".

I decided that, although the model would be based on the literature from a wide variety of sources and on experimental work thoughout the South Australian arid zone, the project should culminate in describing and simulating a particular arid zone paddock. Generalized models are useful for testing and presenting ideas, but they are difficult to validate since there can be no set of detailed validation data. Many important processes in arid zone paddocks have mechanisms that are generally applicable, but the actual outcome is dependent on the exogenous effects at a particular site. This is particularly true in processes involving ~~to~~ the spatial heterogeneity of the paddock.

3.2 *A critique*

Several criticisms could be made of the project. The first is that its scope is too great for one person and the facilities available. Van Dyne (1972) has pointed out that,

> "Probably no one scientist can encompass all the required specialities and knowledge to undertake a thorough study of a complete grassland system".

It is recognised that this is so, but consider also his statement in the same article,

> "In most instances, comprehensive and exhaustive study of the literature is not made prior to the initiation of the field or laboratory research in that area",

and two years later, Norton (1974) in reviewing the achievements of the I.B.P. Desert Biome study, said,

> "The Biome administration has often regretted that it was not possible to spend a couple of years working on the model before embarking on field research".

This project was to pursue these points further, i.e. to review thoroughly (although probably not "comprehensively and exhaustively") the literature and to work on first few cycles of "propose-review- and modify" of an arid grazing model. Whether I, as one scientist, could accomplish this more limited task, can only be judged by this thesis.

The returns from this approach must be much smaller than those from projects such as the I.B.P. Biome studies, but so is the outlay. The funding of I.B.P. has been in excess of $US 40 000 000 per year, (unsigned article in Nature, 248 [1974], 637-638) and the expenditure on several of the Biome projects has exceeded several million dollars per year and has included several hundred man years of labour. The costs of this project were less than four man years and less than $A 10 000 in research funding of all forms.

It is, of course, not valid to directly compare the output and costs of projects of such vastly different sizes, but their relative effectiveness in advancing ecological research should be compared. Tribe (1953) raised a similar question in respect to animal behaviour studies in relation to the whole field of animal production. He recognised that such studies gave further insight into the grazing system, but argued that they were of little predictive value and questioned whether they were the most efficient way of gaining this insight. I believe that animal behaviour studies have since proved their utility (see chapter 8), but similar questions should be asked about the different approaches to modelling. The final assessment can only be made once the I.B.P. projects are more complete, and can be compared with the many other smaller studies.

More extreme criticisms have been levelled at the aims of ecosystem modelling in general. Gifford (1971) had described it as a "depressing" and "pernicious methodology" and as "irrelevant" and demonstrating "the unimaginative sterility" of its practitioners. He sees the need for systems ecologists to de-emphasise quantification and methodology and to re-emphasise problem solving - a point which I think has some validity.

Rothkopf (1973) has levelled similar criticisms at the world models of Forrester and Meadows arguing that,

> "...a model that is constructed without first identifying the questions to be answered is likely to fail".

He criticises the assumption that system dynamics models are the most efficient way of dealing with complex systems, and questions whether there is enough data to build many models. He disagrees with Patten (1972) who argues that models can help create data by the use of iterative fitting and trial and error.

I don't think that these criticisms can be properly answered until systems modelling has been more widely used, and has a longer history of development. However I have borne them in mind in setting out the aims of, and carrying out this project.

3.3 *Problems which might be tackled*

There are many problems associated with sheep grazing in an arid zone paddock which appear to be amenable to a computer simulation approach. These include problems which are in intractable in an experimental situation because the experiment would either be too time consuming, or too costly, both financially and environmentally.

Some of these problems have been 'solved' empirically long ago. For example, Waite writing in 1896 (see Macfarlane, 1968) argued against the common practice of having large paddocks with single water-points and large flocks. This resulted in the over-grazing of the vegetation around the water-point. He recommended that the paddock should be subdivided, with each new paddock having a separate, smaller water-point and flock. He applied this principle on many of his properties, apparently with success (he was the benefactor of the Waite Agricultural Research Institute).

The patterns of grazing around water-points were studied by Osborn et al. (1932) who described four vegetation zones centred on the water-point. The zones were reflected in the vigour of *A. vesicaria*. The A zone, nearest the water-point, suffered a heavy loss of bush, while in the B zone the moderate grazing was reflected as a increase in vigour. The bushes of the lightly grazed C zone appeared to be less vigorous but more dense than the relatively ungrazed bushes of the D zone. This work was carried out in a very dry season and has never been repeated, but there is little doubt of the importance of the ecological unit, centred on the water-point and determined by the ability of the sheep to forage away from it. Lange (1969) called this unit the 'piosphere', and analysed the track pattern within it, while Barker & Lange (1969) analysed the vegetation distribution around the water-point in more detail. There has been little further investigation of the reaction of forage species to moderate and light grazing in the B and C zones reported by Osborn et al. (1932).

Although the importance of the piosphere effect on the vegetation has been recognised by some graziers and most researchers, very little quantitative information about it exists. Barker & Lange (1969) and Barker (1972) described plant density data and plant associations near the water-point, but this is of little direct value to a grazier faced with the prospect of an uncertain return for the expense of re-organizing the station fencing and water supplies. Experimental work on piosphere development and dynamics is very time consuming, and subject to the vagaries of the weather and changes in the paddock management. I decided, therefore, that the grazing model should exphasise the spatial distribution of the impact of sheep on the vegetation. The complete model could then be used to study the development of the piosphere and the effectiveness of different management policies in relation to the use of water-points.

3.4 *Other grazing models*

Throughout this thesis I refer to other models of grazing systems. Not all of the models are of arid zone systems, nor is the list of grazing models discussed exhaustive. The majority of these models had not been published at the start of this project.

I have emphasised these grazing models because there seems to have been little cross-fertilization of ideas, nor transfer of particularly suitable submodels from one model project to another. Many authors have discussed the hierarchical and modular nature of ecosystem modelling, but few have directly applied this in their own models (except, of course, where the model is produced by a team and various components are published separately). I have reviewed the approach used in other grazing system models in each of my submodels and, where possible, I have tried to adopt any approach which seems to be suitable.

The major grazing system models discussed in the later chapters (especially chapters 5 to 9 which describe the submodels) are described below.

Goodall has described (Goodall, 1967, 1969) and has experimented with (Goodall, 1969, 1971) a model of an hypothetical arid zone paddock (probably similar to the Kalgoorlie, W.A. district). As mentioned in section 3.1 his model was intended as a demonstration of the potential of computer simulation rather than to report results. It is one of the few models that deals with the spatial heterogeneity of a system.

Van Dyne (1969a) described a model of an ecosystem including herbivores, omnivores and carnivores. This is still one of the most detailed models reported to date. Since this project was started, Walters & Bunnell (1971) have described a model of deer, sheep and elk management in an area supporting either a forest or grass-forb community. The model was designed to be used as a land management game.

The remaining grazing models discussed here are based on Australian sites. Armstrong (1971) described a model of merino wethers grazing a grassland. This model was begun as an exercise in simulation techniques but later became a design tool for experimental work. Vickery & Hedges (1972) described a model of a *Phalaris tuberosa*/ Trifolium repens (white clover) pasture grazed by merino sheep. Smith & Williams (1973) described a model the early growth of an annual pasture and the liveweight response of grazing sheep. This was validated by comparing it with a grazing experiment originally conducted by Smith.

Swartzman & Van Dyne (1972) discussed the combination of computer simulation with optimization based on linear programming. An hypothetical Australian arid zone system was used as an example. The model dealt with cattle, sheep, kangaroos and rabbits grazing a mixed shrub and herb community. The optimization model dealt with the transfer of stock between two properties and a commons.

3.5 *The aims of the project*

The aims of the project may be summarized as follows.

(1) To gather data (from the literature, by reassessing old records, and from original experimentation and observation) describing the important interactions in the Australian arid zone sheep paddock system.

(2) To determine the most promising approach to at least some of the submodels of components of the system.

(3) To construct a model to describe a particular arid zone paddock and to validate this to the maximum extent possible.

(4) In constructing the model, to bear in mind its applicability to answering some of the major questions facing both station managers, and arid zone researchers.

AN OVERVIEW OF THE MODEL AND SITE

4.0 *Introduction*

This chapter describes the method of tackling the project, the selection of the site to be simulated, and the structure of the rest of the thesis. The project could not be carried out in any strict temporal sequence because of the interrelationships between many of the sections. My first review of the potential of computer simulation applications to arid zone grazing systems was carried out during my B.Sc. Honours year (Noble, 1970, unpublished Honours thesis). This provided an introduction to the literature, and some experience in model building. On this basis it was decided to choose a site at which many of the department's research projects could be carried out, and which would form the basis for the simulation. Work on the various submodels was to proceed in parallel with the field study, with the intention of building a simple grazing model (GRZMOD1) about halfway through the time allotted for the project. This model was intended to test ideas and to demonstrate critical areas before work started on the final model.

4.1 *The selection of the site*

The main experimental site was selected in co-operation with Dr R.T. Lange and Mr M.C. Willcocks. The majority of the Botany Department's arid zone field work had been based at the Koonamore Vegetation Reserve (see section 6.31) which had been in use since 1926. However, it was decided to choose a site on the Roopena group of stations in the Whyalla area (fig. 1.2). This area was chosen because of the excellent condition of the vegetation and the co-operation and facilities provided by the owners.

Wertigo paddock, (33° 10'S, 137° 20'E), on Nonowie Station and 15 km west of Whyalla, was chosen as the main site. This paddock (see fig. 1.2) is 2280 ha in area, flat and mostly clear of tree cover. This meant that it was suitable for the observation of sheep from vehicles and also for a radio-telemetry project envisaged at the time. The contour and drainage map is shown in figure 4.1. The average slope across Wertigo is 0.75% and the detailed internal drainage does not exactly follow the 10 m contour lines. The internal drainage was determined by visual estimation, backed up by some dumpy levelling and observations of the apparent waterflow after heavy rains. The soils of the area have been described by Northcote (1960) and their development by Jessup & Wright (1971). The dominant soil type is a brown calcareous earth (Gc) with loamy surface soils largely free of $Ca\ CO_3$, but with carbonate nodules and travertine appearing deeper in the soil profile (20 cm to 80 cm in Wertigo).

Permanent markers were set up on a half mile regular grid by M. Willcocks for use in several different experiments. This grid was used as a basis for most sampling schemes and was incorporated into the final model (sections 5.47, 6.6 and 8.45). Each marker was taken as the centre of a 800 m x 800 m 'cell' (fig. 8.5) for which separate point models of water movement and storage, and plant growth were included in the final model. Sheep movement and grazing behaviour was modelled on a scale that located any activity as occurring within one of these cells.

The vehicle tracks, fences, water-points and other features of Wertigo paddock are shown in figure 1.2.

The vegetation in Wertigo is mainly an *Atriplex vesicaria* (saltbush) and *Kochia sedifolia* (bluebush) shrubland with other chenopods making a minor contribution to the perennial shrub component. The major ephemerals are the grasses, *Danthonia caespitosa*, *Schismus barbatus*, and *Stipa nitida* and the bassias, *Bassia obliquicuspis* and *B. patenticuspis*. (In this thesis 'ephemeral' plants are taken to include all species which occur regularly in Wertigo, but at times (for example, during droughts) are absent. That is, they have a distinct establishment and die-out stage, even though individuals may survive several years, as do *S. nitida* and the bassias, and therefore would be regarded by some people to be biennials or perennials. These species contrast to the 'perennial' species such as the bushes *A. vesicaria* and *K. sedifolia*. Individuals of these species live several decades and, except under extremely heavy grazing, the species always retains a significant density and biomass). The tree species *Casuarina cristata* (blackoak) and *Heterodendrum oleifolium* (bullockbush) occur in almost pure stands. An open woodland of *Acacia sowdenii* (Western Myall) with a few minor tree species also occurs.

The distribution of the vegetation is shown in figure 4.2. The map is based on ground surveys of Wertigo and biomass readings made in 20 m x 1 m quadrats near the permanent markers in October 1972 and October 1973. The method of estimating biomass is described in section 7.31. This sampling system was not sufficient to allow comparisons to be made between successive readings due to the variability in the vegetation distribution. Either permanent quadrats should have been set up, or larger quadrats should have been used.

The flock management in Wertigo has remained stable over most of its history of use although recently it has come under a new manager. Fixed stocking on the dam water-point has been practised although in unusual circumstances (e.g. lack of water, or bad grass-seed problems) a different water-point has been used, or the paddock has not been stocked. The flock usually consists of 300 to 400 merino ewes. The sheep are removed for a few days for shearing in March and for crutching in September. Lambing occurs in early winter.

4.2 *The GRZMOD1 model*

This section briefly describes the GRZMOD1 model. It is included in the thesis because it was important in shaping the final grazing model.

GRZMOD1 operated on a monthly time increment. The weather pattern was simulated as months of low, medium and high rainfall with the effect of the rainfall on plant growth varying with the month. Two species of perennials, two species of ephemerals, and a litter pool were simulated. The utilization of the paddock by the sheep was modelled in a manner similar to Goodall (1967, 1969). The water-point was central and the paddock was considered to be so large as to be unbounded. The paddock was modelled as a series of annuli centred on the water-point. The utilization of each annulus was inversely proportional to its distance from water and varied with the month, the rainfall, and the amount of forage in the annulus. The sheep body condition was not modelled, but the model stopped if the monthly consumption fell too low.

The model was mainly used for testing the sensitivity of the complete model to changes in the submodels, especially the plant growth and paddock utilization models. Building the model was valuable experience in itself, in both demonstrating the poorly understood or under-quantified areas and in developing modelling techniques.

GRZMOD1 demonstrated the importance of the plant growth and paddock utilization models. The plant growth model was very sensitive to small changes in growth parameters, and these had a major effect on the model as a whole. It was clear from GRZMOD1 that it was essential to include the spatial component in a grazing model, but that an approach different to that of Goodall (1969) was needed. Goodall's approach is essentially empirical, i.e. utilization of the paddock is observed (or estimated) and a function (in tabulated form) is fitted to it. This is modified by one other empirical factor, namely, plant distribution. If a more complete understanding of the spatial behaviour of sheep is to be obtained then the empiricism at the utilization level must be abandoned and a model with more detailed structure substituted. In GRZMOD1 the empiricism was included at the level of separate spatial, climatic and sheep condition factors, as well as the plant distribution factor. In the model described in chapter 8 the empiricism has been reduced mainly to the level of physical and physiological laws. As discussed in chapter 8, the efficiency of the submodel could be improved by reversing the trend and substituting empirical equations in place of some of the more detailed structure.

4.3 *Herbivores other than sheep*

The discussion up to this point in this thesis has emphasised sheep as the main herbivores. GRZMOD1 included only sheep and excluded kangaroos and plant eating insects, the other most obvious herbivores. It also excluded the consumers of dead organic matter since it was not intended to follow complete mineral and nutrient cycles. The main reason for this initial exclusion was the lack of any quantitative knowledge about other herbivores and decomposers. Very little at all is known about the insects of the area, but there appear to be very few species eating live material. Most of the activity is by ants harvesting seeds and litter.

In order to gain a little more understanding of the relative importance of different groups of organisms in Wertigo, an energy flow diagram was derived. This is described in appendix 1.

It was concluded from the energy flow through Wertigo that the herbivores harvest very little of the net primary productivity. The herbivore effect on vegetation is due mainly to their concentration in time or space. The main insect consumers, such as grass-hoppers tend to occur infrequently, but with a paddock wide distribution. If they were to be included in the model it would be as plagues, causing a large amount of destruction throughout the paddock, but at infrequent intervals. This is a possible addition to any grazing model, especially given the work done on the occurrence of grass-hopper plagues by the Waite Agricultural Research Institute at Adelaide (see Andrewartha & Birch [1954] for a summary), however it is not a first priority.

The energy flow diagram did emphasise the importance of the year to year variation in NPP, and the spatial heterogeneity of vertebrate grazing. Kangaroos contribute about 10% of the total vertebrate plant consumption, but probably less than this percentage of total grazing impact. The kangaroos in Wertigo tended to be wider ranging and less dependent on water than the sheep. For example at all times, there were kangaroos using both water-points. They are also soft footed and therefore contribute less to the physical destruction of soil surfaces and plants, and tend to consume mainly ephemerals (i.e. renewable resources) (Griffiths & Barker, 1966; Storr, 1968; Chippendale, 1968; Bailey et al., 1971). In bad droughts kangaroos will migrate to better pastures. Therefore it seems that the impact of kangaroos is very much less than that of sheep, and that kangaroos may be omitted from at least the first grazing model. The dung distribution data collected by Lange and Willcocks (section 8.53) further support this conclusion. They showed (pers. comm.) that the dung distributions of sheep and kangaroos tend to be negatively associated, which means that the kangaroo's grazing impact will be in areas lightly used by sheep.

4.4 *The model structure*

This section describes briefly the structure of the final model (GRZMOD2) and the method and sequence of approach to the submodels. I present only the final model structure, with little reference to the 'evolutionary process' by which it was developed. Some of this detail is included in the submodel descriptions in subsequent chapters, but much is omitted. For example the sheep movement model presented in chapter 8 is the fourth of a series of approaches. The first was the model used in GRZMOD1, which itself was a development from that of Goodall (1967, 1969). A simple diffusion model based on random walk theory was then tried, but this was later replaced (or developed into) a Markov model. In the Markov model, the probability of moving from one cell to another and one activity to another was described by Markov matrices. The Markov probabilities were functions of several parameters. This model finally developed into the model presented in chapter 8. There has been a tendancy throughout the building of the final model for the formal structure to be hidden as more interactions are added, and as submodels are brought together. This is unfortunate in the sense that it makes the model structure difficult to follow, and the submodels difficult to modify or replace. Although there are many advantages in maintaining simple structures, or mathematically formal approaches (c.f. Patten's [1972] argument for linear models), it must be recognised that this will not completely describe real biological systems. The success of the model will be judged by whether it fulfills its aims.

The main submodels and some important parameters are shown in figure 4.3, using a notation similar to that of Forrester and Meadows (e.g. Forrester, 1971). The heavy lines represent the flow of a particular substance while the lighter lines represent the flow of information. The model is mainly concerned with the flows of water, nutrients (here represented by nitrogen), and carbon (actually organic matter) through the ecosystem. The nutrient flow is shown in more detail in chapter 6.

Many other interpretations of the paddock ecosystem are possible and the reasons for the particular structure adopted here are described in the following chapters. However many decisions regarding detail and approach must remain arbitrary. One of the most important decisions is the basic time increment to be used. It was decided to adopt one day, since this is the most important natural division of time in the ecosystem. However, being an important natural unit is not sufficient justification for its adoption. The time increment must also be of a scale appropriate to our present understanding and management of the system. No manager of a sheep station attempts to revise his policy on a daily basis and time increments as long as one week (c.f. Swartzman & Van Dyne, 1972) or even a month would be adequate. Obviously, models with a shorter time increment are still suitable bases for experiments with management policies, but they would be inefficient if this were their only purpose. A one day time increment is also sufficiently fine resolution for the soil moisture, plant growth and animal physiology models, given our present understanding of these processes. A period of about one week (or the more useful 'pentad', or five day period) might be more efficient. However, it appeared that the sheep movement and behaviour model would require a time increment of a maximum of a day, and probably even less. Therefore all the major processes were modelled on a daily basis. The sheep movement and behaviour model operated on an hourly time increment during the times sheep were active, but returned summarized results for each day.

The choice of the time increment prescribes much of the model structure and submodel approach.

4.5 *Approach to the project and model*

The South Australian arid zone, like many other arid zones, has a highly variable weather pattern, with irregular seasonal patterns. Therefore, models of arid zone ecosystems must be able to be run for a period of many years if they are to be of much aid in understanding and managing the ecosystem. For example, Swartzman & Van Dyne (1972) used runs of a decade in comparing management schemes for an arid zone station.

Unfortunately long term studies are as rare in arid zone ecosystems, as in other ecosystems. Two of the most applicable studies carried out in Australia were conducted areas similar to Middleback.

The most intensive arid zone grazing study carried out in Australia, was the Yudnapinna experiment. The experiment ran from 1938 to 1951 on Yudnapinna Station, 100 km north of Middleback and in very similar vegetation. Thirteen plots of 160 acres (65 ha) were grazed at different stocking rates by merino sheep from 1941 to 1951, and edible green forage was estimated in the spring of each year. Sheep live weights and wool production were also recorded. However, despite the effort and expense of this experiment it was very poorly reported. There exist only three papers describing the experiment. Woodroffe (1941) described the setting up of the experiment, while the only papers reporting any of the results are a brief summary in Trumble (1952) and in more detail by Trumble & Woodroffe (1954).

This paper presented only a small portion of the results, and the treatment of the data and the conclusions drawn were very badly handled. This is potentially a very important paper since it seems to indicate that heavy grazing may stimulate bush growth, and it is discussed further in appendix 2.

Another long term study in the South Australian arid zone is being conducted by the Adelaide University Botany Department at Koonamore Vegetation Reserve (K.V.R.) (see section 6.31). At this site, the enclosure and regeneration of a previously over-grazed *A. vesicaria* - *K. sedifolia* pasture has been monitored since 1926. This has been well reported by Osborn (1925), Osborn et al. (1935) and Hall et al. (1964). There is, however, a large amount of information, especially in the form of photo-points, that has been little used. Some of this information has been used in this project and is discussed in section 6.3. There are of course, no animal records associated with K.V.R.

No other studies, both of sufficient length, and of sufficient similarity to the system being modelled, are known to exist. This means that a validation of the complete model in the normally accepted sense is not possible. Instead each submodel has been derived and written as a virtually independent entity, and has been independently validated as much as is possible. It has only been possible to apply Turing's test to the final model.

These restrictions have also governed the experiments conducted with the final model. Some runs have been done to allow the results to be compared with well known, but usually non-quantified, processes (an application of Turing's test). Other runs have been performed in order to investigate the sensitivity of the model to important parameters such as rainfall. However detailed sensitivity analyses have not been done. Given the incomplete validation of the final model (and of some of the submodels), sensitivity analyses could be best applied to the separate submodels. However there has not been time to do this. Nor have any major experiments, conducted along the 'proper principles of experimental design', been attempted, again because of the incomplete validation of the model as a whole and a lack of time. It has been considered more important throughout this project, to concentrate on the submodels, and to bring these together into a final model, than to experiment with the final model itself.

4.6 *Thesis structure*

The thesis structure was outlined in figure 1.1 The first two chapters were intended to give the necessary review of the two main fields of science brought together in this thesis, i.e. arid zone ecology, and computer simulation. Chapter 3 discussed why this project was attempted and chapter 4 broadly outlines the specific site studied and the model structure.

Chapters 5 to 9 describe the different submodels. Each chapter is self contained and cross references are made both forwards and backwards throughout them. Literature reviews are included immediately before the appropriate sections, and are limited to the information taken into account in building the model.

Chapter 10 describes the bringing together of the submodels to form the final model, while chapter 11 describes the experiments performed on it. Chapter 12 is a final review of the project.

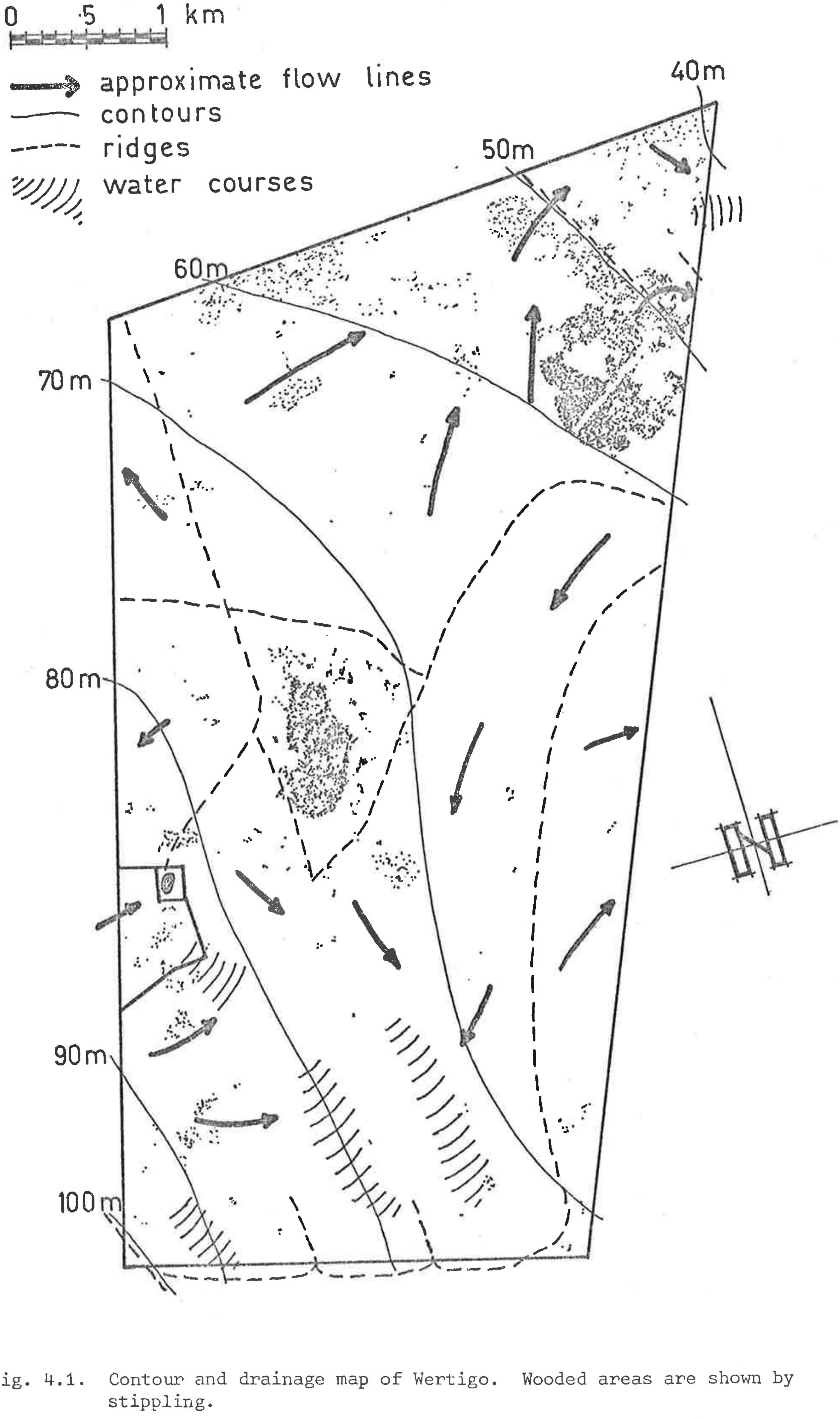


Fig. 4.1. Contour and drainage map of Wertigo. Wooded areas are shown by stippling.

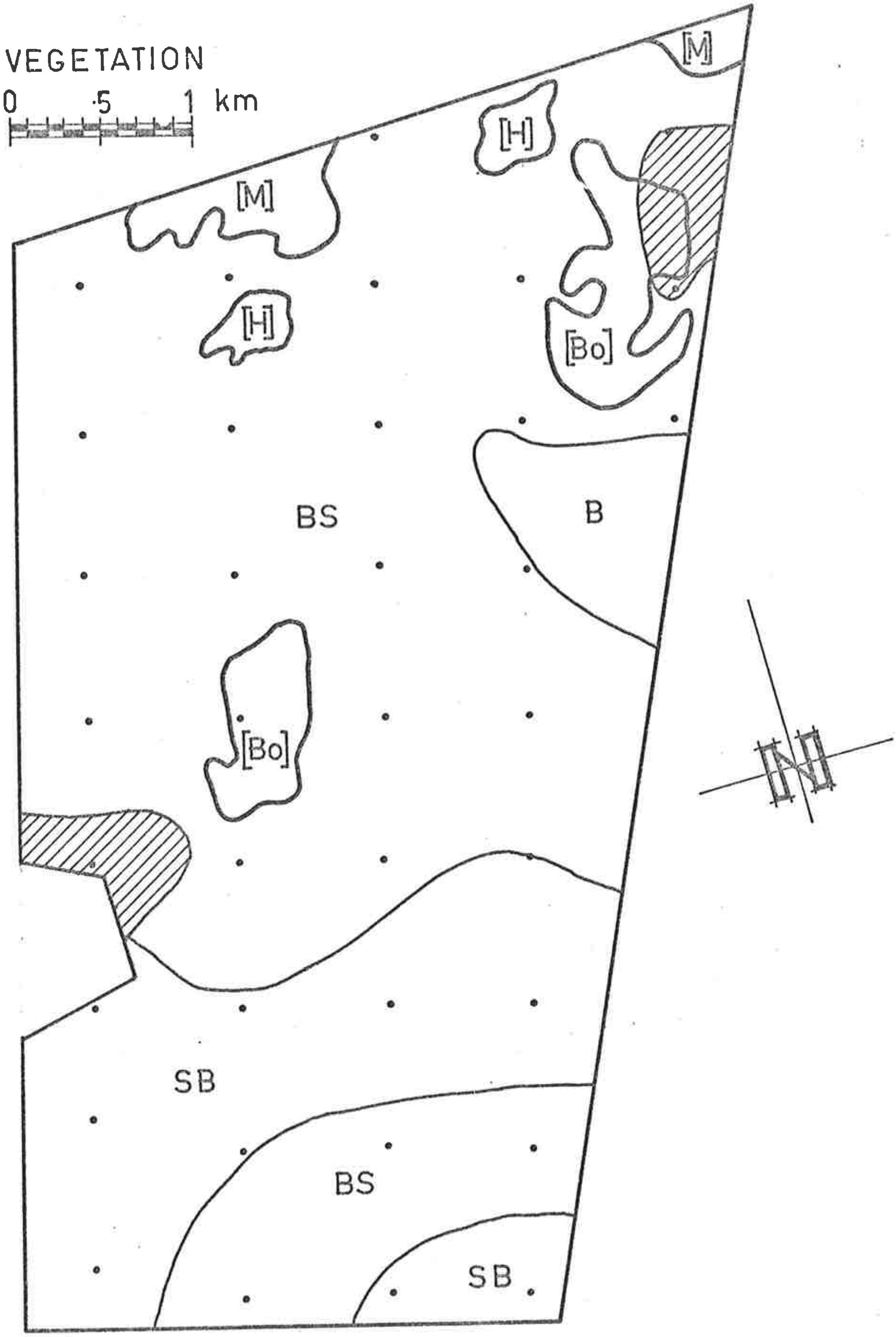


Fig. 4.2. Vegetation map of Wertigo. The major wooded areas are indicated by [Bo], blackoak; [H], *Heterodendrum*, and [M], myall. S and B represent saltbush and bluebush respectively, while SB and BS represent mixed stands with saltbush and bluebush dominants respectively.

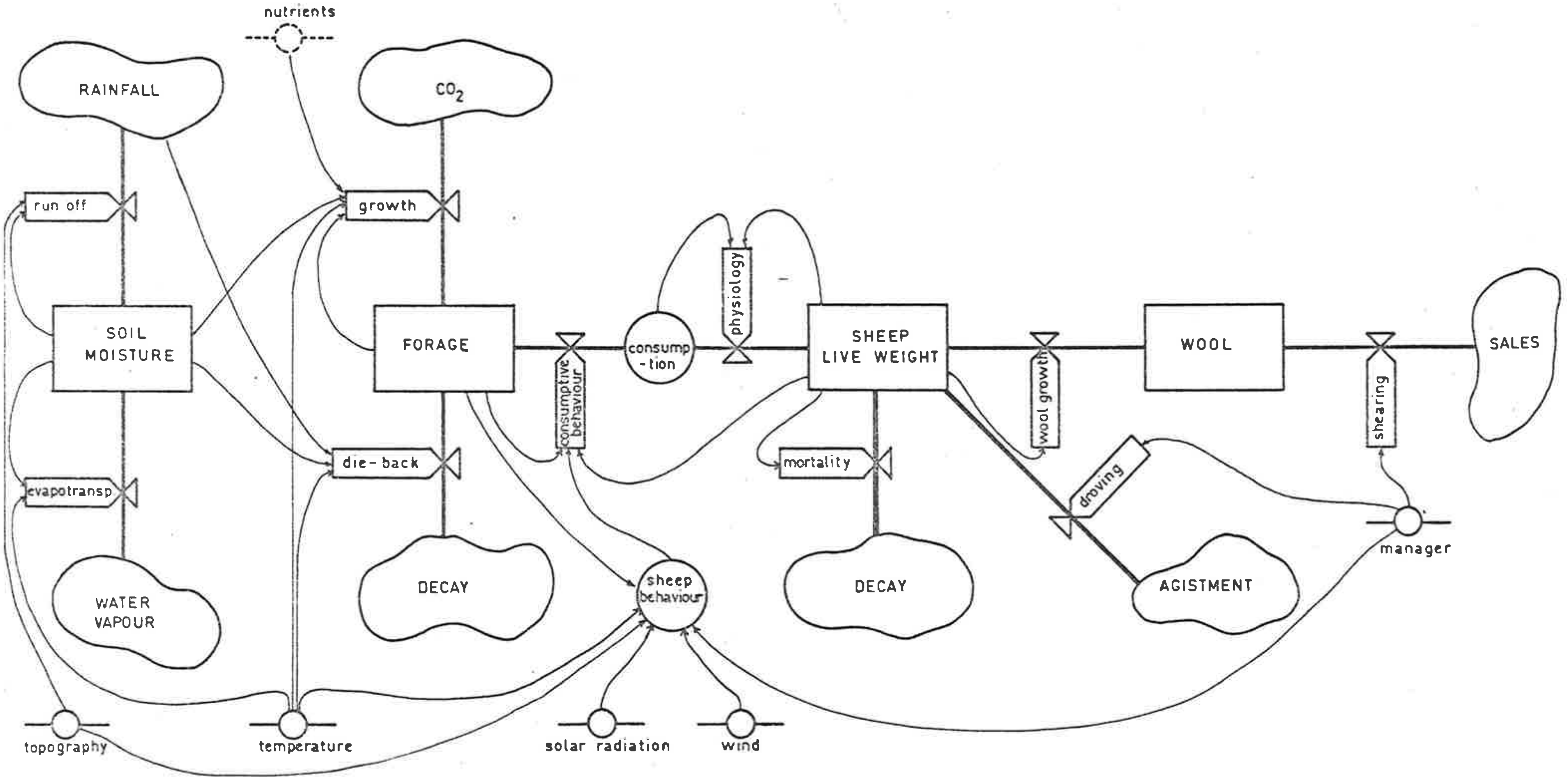
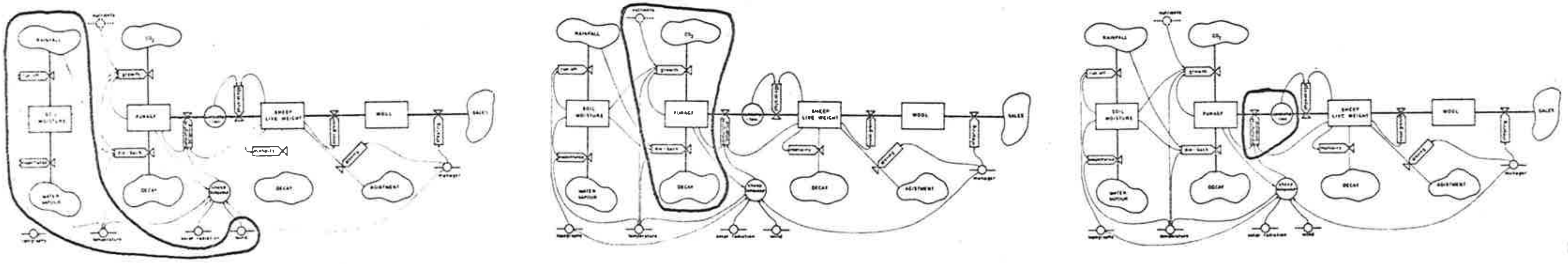


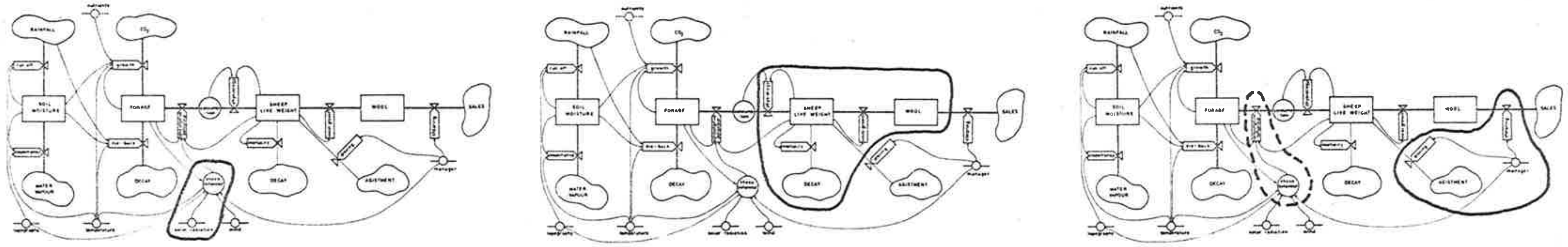
Fig. 4.3a. A diagram of the complete model using notation similar to that of Forrester (1971). The heavy lines represent the flow of water (left hand side) and carbon products (right hand side).



Chapt. 5 - climate

Chapt. 6 - plant growth

Chapt. 7 - consumption



Chapt. 8 - movement & behaviour

Chapt. 9 - sheep physiology

Chapt. 11 - Management [———]
and new sheep breeds [-----]

Fig. 4.3b. A diagram showing the section of the complete model dealt with in each of chapters 5 to 9 and chapter 11.

CLIMATE

5.0 *Introduction*

This chapter describes the submodels needed to simulate the meteorological driving variables used in the project. All the necessary driving variables are stochastically generated by the final model itself, and no meteorological records are required as inputs. However each of the submodels can be replaced by a set of records if necessary.

This chapter describes the rainfall, evapo-transpiration and associated soil moisture submodels, as well as the air temperature and wind submodels. Solar radiation is directly involved only in the sheep behaviour submodel and it is described in chapter 8.

5.1 *Approach*

The simulation of meteorological variables is a new field, mainly because there was little call for it before large simulation models were built, nor were the computers necessary for the derivation and execution of the models available. However there has long been interest in various agrometeorological and climatological indices for both descriptive and predictive use. Although these indices were the fore-runners of the simulation approach, the techniques for deriving them are of little direct use in deriving models.

Meteorological models can be constructed to simulate the climate at various scales. This thesis includes models operating at a micro-meteorological (e.g. the sheep heat balance) and meso-meteorological scale (e.g. the rainfall model) (see Munn [1970] for a discussion of meteorological scale).

Many different models, simulating single processes such as rainfall or air temperature, have been published. These models usually deal with the autocorrelation of these variables via Markov chains, spectral analysis, or some other technique. However few papers deal with the correlations between the processes. For example, there is a positive correlation between air temperature and solar radiation. This correlation can be shown to exist for total daily solar radiation received and mean air temperature, but when hourly data are compared the correlation is less pronounced. Gringorten (1966) has attempted to treat groups of climatic parameters as part of a single Markov process, but, as Sharon (1967) has pointed out, this approach becomes very complicated when several cycles (such as diurnal and annual cycles) are imposed on the system. Recently (and well after the climatic submodels for this project were written), Durmont & Boyce (1974) described a method for simulating daily rainfall, maximum and minimum air temperature, vapour pressure, amount of sunshine and wind run. They linked rainfall, temperature and vapour pressure in the model, but sunshine and wind meteorological data showed no correlation with the other variables and were modelled independently. I recognised throughout the construction of the climate models for this project that an approach similar to Durmont & Boyce was needed, but I had neither the time nor data to attempt it.

5.20 *The rainfall submodel*

Rainfall events are of major importance in arid ecosystems although rainfall itself has little direct interaction with the plants or animals in the ecosystem. Any interactions are generally via edaphic variables such as soil moisture or runoff, or via correlated variables such as humidity or reduced insolation.

Three approaches to the generation of rainfall data can be used in model building (and these approaches are also applicable to other forms of meteorological modelling). The first is to use an actual historical record. Such an approach is an important device for testing the rest of the model for validation purposes against a known historical record including both driving variables and derived variables. However the use of a particular historical record has little else to recommend it since the selection of the actual sequence to be used represents only a sample from a longer process. It lacks the generality and "depth of insight" (Watt, 1968, p. 5) necessary for useful model building.

The second approach is to sample from a set of historical data. For example the rainfall record for a particular January month may be chosen at random from an historical record to simulate the January rainfall in the model. Similarly a February rainfall record is chosen at random to simulate February in the model and so on. This method has two serious weaknesses. Rainfall is a stochastic process and any historical sequence unless very long, will lack smoothness, leading to the over - or under - generation of certain rainfall events. Second, the actual sequence of rainfall periods may not be independent, especially if periods as short as hours or a day are being used. This implies that some model must be developed to account for the observed interdependence of rainfalls, and this leads to the third approach.

The historical record can be used to develop a model of the interdependence of, and amount of rain falling in rainfall events. This approach has the advantages that unlimited numbers of realistic rainfall sequences may be generated and the insight gained into the rainfall process may have other useful applications.

The main factors to be considered in a rainfall model are, (1) the sequence of wet and dry periods, (2) the amount of rain in wet periods and (3) the spatial and temporal extent of the fall. The latter factor is relevant in models where there is a spatial heterogeneity of rainfall over the area being modelled, or where one is interested in runoff, water catchment or erosion events. These are all important in the paddock model but have not been incorporated as yet. In the present paddock model the rainfall is assumed to be uniformly distributed over the area and to occur early in the day. Runoff is related only to the total daily rainfall. This leaves the first and second factors to be modelled.

The sequence of wet and dry periods was originally investigated by Newham (1916) who demonstrated a persistence of wet and dry spells in English data. The first mathematical model to describe the sequence of wet or dry days was that of Gabriel & Neuman (1962) using data for Tel Aviv. They used a two state, first order Markov model to describe persistence between successive wet days. Weiss (1964), using data from North American sites, supported the Markov model, but Wiser (1965) found that the model had to be extended to an approximation of a higher order Markov model. Fitzpatrick & Krishnan (1967) analysed the rainfall for five day intervals for six central Australian sites. They found that first order Markov model gave better agreement than a random model.

There has been little work done on the amount of rain falling in wet periods. Kotz & Neuman (1959) showed that there was auto-correlation between rainfall amounts for periods of one day but there was no significant auto-correlation for longer periods. Hannan (1955) also demonstrated auto-correlation between daily rainfall amounts. Das (1955) fitted a truncated gamma distribution to the daily rainfall amounts recorded at Sydney, while Zwack et al. (1969) fitted a similar distribution to monthly rainfall for New Jersey.

Pattison (1965) described a model of an hourly rainfall process for California. He found that the first order Markov model was not sufficient since it failed at the transition between wet to dry hours. It was necessary to use a sixth order Markov chain for wet periods and a first order elsewhere. He modelled rainfall amounts as a 20 state Markov chain.

Cole & Sherriff (1972) described a model covering persistence, amount, and spatial distribution of rainfall for a catchment in North Wales. Wet and dry sequences were generated by sampling from empirical distributions of each sort, while a first order Markov chain model was used to generate rainfall within a wet spell. They used historical data to construct histograms of the amount of rain for (1) solitary wet days, (2) the first day of a wet spell and (3) the remaining days of a wet spell. The rainfall was sampled directly from these distributions. They also pointed out that a regression of daily rainfall on the rainfall of the previous day is not valid because the variance of the residuals about such a regression is not constant. One of the models tested for the paddock model was broadly based on the Cole & Sherriff model.

5.21 *Models used in other simulations*

Although rainfall events are of major importance in arid ecosystems, in more mesic areas it is possible to ignore individual rainfall events. Some models, therefore do not include rainfall as a driving variable. Walters & Bunnell (1971) used only a growth season. During this season plants grew at their maximum rate, unless limited by competition. There was no variation between different years in the maximum growth rate. Van Dyne (1969b) proposed a model using solar radiation as the driving variable. This assumed that soil moisture was never limiting during the potential growth period. In another model Van Dyne (1969a) apparently used historical rainfall data.

Many other models do not include a complete description of the rainfall variable. Armstrong (1971) and Vickery & Hedges (1972) apparently used historical data. Swartzman & Van Dyne (1972) have no clear description except that they used a "probalistic climate generator" apparently generating weekly rainfalls with a variability similar to that observed in the field.

Goodall (1969) generated rainfall by randomly sampling from two cumulative frequency distributions of 19 classes of daily rainfall amount. One distribution was used if the previous day was wet, and another if the previous day was dry (i.e. a first order Markov chain model). A different pair of distributions were used for each month of the year. The actual rainfall amount is uniformly and randomly distributed within the class.

Few authors appear to have given much attention to the modelling of rainfall, and few reviews exist. Pochop (1969) reviewed some of the approaches that could be made, but most modellers have preferred to use historical data despite the short comings as pointed out in section 5.20.

5.22 *The Middleback rainfall model*

Middleback Station is in the Whyalla Meteorological Bureau region which is the topic of the "Climatological Survey - Region 13 Whyalla, South Australia" (Bureau of Meteorology, 1961). The region is on the northern edge of that area of South Australia with a winter rainfall maximum. This maximum is only apparent in the number of wet days per month, which show a mean of less than 2.0 wet days per month in summer and 3.0 to 4.0

in winter. The monthly rainfall amounts are approximately equal, with the exception of February (See fig. 5.1). This region is sometimes affected by rain from tropical cyclones moving down from the north. Since 1901 heavy falls (300 - 600 pt) have been recorded in February 1921, 1946, 1950 & 1973. These falls are discussed further below. The mean annual rainfall in the region varies from 750 pt (190 mm) to 1100 pt (300 mm).

Daily rainfall for the period 1925 - 72 was obtained from the owner of Middleback Station. The rainfall was recorded at the homestead, 8 km from Wertigo paddock. Middleback station is not an official Meteorological Bureau recording site, however data collection has been regular and apparently accurate. The nearest official recording site is Whyalla which is 25 km from Wertigo, and much closer to the coast. The data have been recorded in Imperial units (pt) and these have been retained throughout the analysis. They are converted to metric units as a final step in the simulation programs. The major rainfall variables are summarised in figures 5.1 and 5.2.

The data was first examined for auto-correlation between daily rainfall events. Middleback has a mean daily rainfall of 2.08 pt (0.53 mm) and only 1391 out of the 17520 days* (48 years) of records have greater than the mean daily rainfall.

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*Throughout these analyses February 29th has been ignored in leap years. This means that all years have 365 days. Of the 12 days ignored in the rainfall record none had any rain.

The marked skewness of the daily rainfall distribution means that most parametric test are unreliable. Hannan (1955) pointed out that estimates of the variance of the correlation coefficient assuming normal distribution would under-estimate the actual variance of the skewed distribution. The non-parametric Wald - Wolfowitz test (Phillips, 1971; Siegel, 1956) was used to test the daily rainfall for lags of 1 to 5 days for randomness (fig. 5.3). There was a significant correlation between rainfall on successive days at Middleback, as was shown by Hannan (1955) for Sydney and Kotz & Neuman (1959) for Tel Aviv. There was also evidence of some auto-correlation between the two day lag periods. This was further investigated by calculating the auto-correlation coefficients for lags of 1 to 5 days

lag k	r_k	r_1^k
1	0.213	
2	0.133	0.045
3	0.059	0.009
4	0.083	0.002
5	0.076	0.000

If there was no auto-correlation between days with a lag of greater than one, then $\rho_k = \rho^k$, where k is the lag. For the two day lag, $r_1^2 = 0.045$ was compared with $r_2 = 0.133$. There appeared to be a greater auto-correlation between 2 day lags than would be predicted by the auto-correlation between successive days alone.

This indicated that a second order Markov model may have been needed in a rainfall model, although a first order Markov chain would possibly be a suitable, but imperfect, basis.

Wiser (1965) described a modification of the Markov process to allow for contagion, while Lowry & Guthrie (1968) described a method of fitting and testing Markov chains of order greater than one. Either of these methods could have been applied, but since the only requirement of the rainfall model was that it produced adequate artificial rainfall data for the other sections of the paddock model, a first order model was tested first.

As mentioned above, Goodall (1969) used a 2 state, first order Markov chain for each month to simulate rainfall. The second state (i.e. the wet days) was subdivided into 18 classes representing different rainfall amounts. Data were collected from the Middleback rainfall to build a similar model. However the rainfall events were too sparse to allow 18 subdivisions of rainfall amount. Either a function could have been fitted to the data and the resulting smoothed distribution used on the model, or the class intervals could have been grouped into broader classes.

An incomplete gamma function was fitted to the distribution of all wet days by the method of Thom (1958), as outlined in Zwack *et al.* (1969) the function is

$$G\,(x) = \rho + (1 - \rho) \int_0^x \frac{x^{\gamma-1}\, e^{-(x/\beta)}}{\beta \quad \Gamma(\gamma)}\,dx \qquad \text{(E5.1)}$$

where $G\,(x)$ is the cumulative probability of x, ρ is the probability of zero values, γ is the shape factor of the distribution, and β the scale factor of the curve. The values of ρ, γ and β were estimated and the function was evaluated by Simpson's rule. The fitted function (fig. 5.4) was readily shown to differ significantly from the actual data (χ^2_{12} = 119.5 and Dmax for η = 1440 was 0.070 for the Kolmogorov - Smirnov test, both of which have $P << 0.01$).

At this point it was necessary to examine the accuracy with which the original rainfall data were collected. In some rain gauges low rainfall events may be innaccurately measured and sometimes light falls (e.g. a few points at night) may not have been noticed and hence not actually recorded for that day. The figure 5.4 data show a smooth curve indicating that there were no serious errors in readings while figure 5.5 shows a more detailed analysis of the critical light-fall readings. This shows that there was a tendency to read round numbers (5, 10, 15, 20) rather than the numbers either side, and there appears to be too few low rainfall (<5pt) events recorded. If these were indeed errors in the rainfall readings then the corrected values (from extrapolation by eye) are shown in figure 5.5. They indicate that the actual mean number of wet days per year should be increased by 3.0 days to 33.0 and the mean annual rainfall by 4.8 pt (1.2 mm) to 763 pt (194 mm). These adjustments would have little effect on the building of the model, with the exception of the fitting of the gamma function and other such curves.

At this point it was decided to construct the model by grouping some of the class intervals. This had the advantage of requiring less computer memory than the original description and also of being faster than the evaluation of the gamma function. The class intervals adopted were 0 pt, 1 - 9 pt, 10 - 19 pt, 20 - 49 pt and ⩾50 pt. For small class intervals it is sufficient to distribute the actual rainfalls generated by the model uniformly at random across the class intervals (c.f. Goodall, 1969). This would give a mean simulated fall of 5.0 pt in the 1 - 9 pt class interval compared with an actual mean of 5.3 pt (or 4.5 pt for the data corrected for gauge error). For the 10 - 19 class interval the mean simulated fall is 14.5 pt compared with an actual mean fall of 13.3 pt. These differences would only cause a mean error of approximately + 20 pt (5.1 mm) per year.

A more accurate description of the distribution was needed for the 20 - 49 pt class interval as well as for generating falls of greater than 50 pt. The incomplete gamma function could have been fitted to the data, this time with the data truncated at <20 pt rather than <1 pt as previously. However a similarity was noted between the cumulative distribution of daily rainfalls excluding dry days (fig. 5.4), and the general class of curves,

$$\text{(E5.2)} \qquad y = a - b * \exp(- c * x)$$

It may be shown that as the shape factor $\gamma \to 1$ the incomplete gamma function becomes;

$$G(x) = \rho + (1 - \rho) * \int_0^x \left[(x^{\gamma - 1} * \exp[-x / \beta]) / (\beta^{\gamma} * \Gamma[\gamma]) \right] dx$$

$$= \rho + (1 - \rho) * \int_0^x \left[\exp(-x / \beta) / \beta \right] dx$$

$$= \rho + (1 - \rho) * \Big[-\exp(-x / \beta) \Big]_0^x$$

(E5.3) $G(x) = \rho + (1 - \rho) * (1 - \exp[-x / \beta])$

Since on using Thom's method to fit the incomplete gamma function γ was 1.074, then $y = 1 - \exp(- c * x)$ was seen to be a suitable approximation. This function has the advantage of being quick to evaluate and of being easy to fit since it is readily linearized.

i.e $y = 1 - \exp(- c * x)$

therefore

(E5.4) $\ln(1 - y) = - c * x$

The parameter c was estimated for falls in the range 20 - 49 pt and for falls > 50 pt (fig. 5.6). Rainfalls could be generated by using the transform,

(E5.5) $x = - \ln(1 - z) / c$

where z is a uniformly distributed random number and $0.0 \leqslant z < 1.0$ and x is the rainfall in points.

A model using a first order Markov chain with 4 divisions of rainfall was constructed. The Markov matrix data is given in table 5.1. A Markov matrix was calculated for each month, however the same equation 5.5 was used for all the months. This simulation was run for 480 years and was compared with the 48 years of actual rainfall data.

The mean annual rainfall of the simulated data was 782 ± 10 (SE) pt (199 ± 3 mm) compared with the actual mean of 759

± 25 pt (193 ± 6 mm). There is no significant difference between the means (non-pooled t test) but the variance of the simulated rainfall is significantly greater than the actual variance ($F_{479/47} = 1.62$, $0.01 < P < 0.05$). The distribution of annual rainfalls is shown in figure 5.2. There is no significant difference between the cumulative distributions of the actual and simulated rainfall as tested by the Kolmogorov - Smirnov two sample test (Siegel, 1956). The actual data showed an extreme peak in the 700 - 800 pt class interval (c.f. the lower variance than that of the model), but it does not differ significantly from a normal distribution with the same mean and variance ($\chi^2_4 = 3.2$ and $D_{max} = 0.073$ in the Kolmogorov - Smirnov test, both of which are non-significant).

The numbers of wet days in a month are very similar for both the actual and simulated rainfalls. However the monthly rainfalls indicate that the model tends to over estimate the amount of rainfall in the "winter" months (May to October) while, with the exception of December, under-estimating the rest. This may be a result of using the same equation 5.5 for both summer and winter months. In winter there are more small falls, with heavy falls (>80 pt, or 20 mm) being rare, while heavy falls are more frequent in summer. The very low estimate for February was probably a result of the model not accounting for the tropical cyclones mentioned earlier.

The model was modified to use different constants in equation 5.5 for "summer" and "winter" months (fig. 5.7).

A section was added to simulate the tropical cyclones in February. The 'Climatological Survey' for the region (Bureau of Meteorology, 1961) mentions 3 such storms in the period of approximately 1900 to 1960. Another storm occurred in 1973. These brought from 300 to over 600 pt on each occasion. They were modelled by allowing a fall, uniformly and randomly distributed between 300 to 700 pt, to occur in February with a probability of 0.05. There could be only one such fall in a year.

This simulation was also run for 480 years. The mean was 798 ± 12 (SE) pt (203 ± 3 mm), which does not differ significantly from the actual mean, but again the variance was significantly greater than the actual variance. The cumulative distributions of the annual rainfalls did not differ significantly when tested by the Kolmogorov - Smirnov test.

The modified model still over-estimates the rainfall in most months. This is probably due to the approximations used in the 1 - 9 pt and 10 - 19 point rainfall classes. The February rainfall estimate corrected for tropical cyclone effects was much nearer the actual rainfall. There was no significant difference (Kolmogorov - Smirnov test) between the actual and simulated distributions of amount of rain on a wet day, the amount of rain in a wet spell nor the length of wet spells. A wet spell was defined as a sequence of 1 or more days each of which recorded some (> 1 pt) rainfall. The year was divided into 73 'pentads' of 5 days and the distribution of the amount of rain in each of these examined. Again no significant difference was detected by the Kolmogorov - Smirnov test.

This model is adequate for the purpose of the paddock simulation. It differs significantly from the actual data only in the variance of the annual rainfall. The difference between actual mean annual rainfall and simulated rainfall is neither statistically significant, nor important since it must be realised that if the actual mean annual rainfall is recalculated for the 50 years from 1925 to 1974, the mean annual rainfall is increased from 759 pt to 804 pt (204 mm) due to the heavy rains of 1973 and 1974.

However a second model, based on the work of Cole & Sherriff (1972), was tested simultaneously. It was apparent from the historical data that the Middleback area was subject to isolated showers (i.e. single wet days) with rarer wet spells. An analysis showed that 68% of all wet days occurred as solitary wet days, and since Cole and Sherriff model such days separately, an approach similar to theirs was adopted.

The probability of a dry day (P_d), the probability of a solitary wet day (P_s) and the probability of a wet spell following any dry day (P_w) were found for each month. The distributions of the rainfall amounts for solitary wet days and the first wet day of a wet spell were calculated for each month. The transition probabilities of the second and subsequent days of a wet spell were also calculated for the 0 pt, 1 - 9 pt, 10 - 19 pt, 20 - 49 pt and > 50 pt class intervals for each month. These distributions were still too sparse to be used in the model since only 198 wet spells were recorded in 48 years. The monthly data were therefore pooled to give data for each of the four seasons. Rainfalls were distributed within class intervals as in the previous model and the tropical cyclones in February were also modelled. This model differs from that of Cole & Sherriff in that the lengths of wet and dry spells are generated from the transition probabilities of the rainfall distributions (e.g. a wet spell ends when a 0 pt rainfall is generated) and not from a separate distribution of the length of wet and dry spells as in the Cole & Sherriff model.

This model was also run for 480 years. The simulated mean annual rainfall was 772 ± 12 (SE) pt (196 ± 3 mm) compared with the actual mean of 759 ± 25 pt (193 ± 6 mm). There was no significant difference between the means, but again the variances differed significantly ($F_{479/47} = 2.29$, $P < 0.01$). The distribution of annual rainfalls is shown in figure 5.2. The same tests as used for the model described previously were again carried out. The Cole & Sherriff model did not differ significantly from the actual data except in the case of the distribution of the lengths of the wet spells that were actually recorded. Since the modified Cole & Sherriff model was also slower to execute on the CDC6400 and required more memory space, the model based on Goodall's work is used in the complete model.

The observation that the modelled and actual annual rainfall variances differed significantly is still unresolved. One would expect the modelled annual rainfall to show a smaller variance than the actual variance. This would be due to the transition matrices used in the model being constant whereas in the real situation, they themselves vary, so increasing the variance. It should be noted however that the variance in annual rainfall at Koonamore Station is greater than that at Middleback Station. This indicates that the low variance of the Middleback Station rainfall may be due to some, as yet undescribed, meteorological phenomena, or simply to chance.

5.3 *Air temperature and cloud cover*

Air temperature is important in both the plant growth submodel and the sheep movement submodel. The plant growth submodel requires only an estimate of the daily mean or maximum temperature, while the sheep movement submodel requires that the diurnal cycle be modelled as well. It is also important that the solar radiation input, as affected by cloud cover, should be correlated with temperature, since air temperature and solar radiation load are important in determining the sheep heat balance.

The annual and diurnal temperatures follow a curve that may be described by a Fourier series, and many such relationships describing the variation of average air or soil temperature with time have been published (Prescott, 1942; West, 1952; Bingham, 1961; Jordan et al., 1968; Mottershead, 1971). Usually a two or three term series is sufficient to describe either the annual or diurnal cycles of such variables as mean maximum, minimum or range.

In most grazing models the temperature data is usually input as an independent exogenous variable, generated either by a Fourier series or from actual data. This approach was not considered for this model since numerous long runs of data were needed. It was also important in the sheep movement submodel to include both the within day variation and the variation from day to day in air temperature. This also had to be correlated with solar radiation input via cloudiness.

The mean monthly maximum and minimum temperatures at Whyalla (Australian Bureau of Meteorology, 1961) may be adequately described by simple sine curves (i.e. one term Fourier series),

$$\text{(E5.6)} \qquad TE_{max} = 23.3 + 6.2 * \sin [(110. - DAY) * 360/365] \quad \ldots\ {}^{\circ}C$$

$$\text{(E5.7)} \qquad TE_{min} = 12.1 + 5.8 * \sin [(110. - DAY) * 360/365] \quad \ldots\ {}^{\circ}C$$

where DAY is the day number of the year and the term in square brackets is in degrees of an arc.

In southern Australia a succession of periods of gradually rising temperatures followed by sudden cool changes associated with the easterly movement of pressure systems, is superimposed on the annual temperature cycle. The cool changes (or cool fronts) bring a change in wind direction and an increase in intensity, accompanied by a sudden fall in temperature of 5 to 20°C (Loewe, 1945; Berson et al., 1957, 1959). These fronts have a mean frequency of 6.8 days in South Australia (Specht, 1972).

The daily minimum air temperature and temperature range are modelled as follows. After a cool change, TE_{min} and

TE_{range} are set to a value specific to the month (table 5.2). These values are then altered by a random amount varying between -2.4 and 3.6 °C. This random change is repeated daily to establish the minimum temperature and range for that day. At the same time, the probability of a cool change is increased from 0.0 in steps of 0.03 per day to a maximum of 0.8. The probability is compared with a random variable each day to see if a cool change has occurred.

The diurnal cycle is modelled as follows. It was observed that the hottest time of the day was about 15.00 hrs C.S.T., while the coolest time was about 6.00 hrs C.S.T. The temperature cycle is modelled by a sine curve with a period of 18 hours and a maximum at 15.00 hrs (and therefore a minimum at 6.00 hrs), and an amplitude equal to the temperature range. Between 20.00 hrs and 6.00 hrs the next morning, the fall in temperature is linear. Figure 5.8 compares the recorded temperature on clear summer and autumn days at Middleback and the temperature predicted by the model set to have the same minimum and range.

The model gave mean monthly maximum and minimum temperatures similar to those reported for Whyalla (table 5.2). The standard deviation of the daily maximum temperature for each month of the simulated data was approximately 6.3 °C, which is similar to that recorded at Yudnapinna and Koonamore, and also to results elsewhere in the world (Bingham, 1961). The mean time between simulated cool changes was 6.9 days compared with 6.8 days reported by Specht (1972).

The solar radiation input is linked to temperature via cloud cover. This is not an entirely satisfactory solution since the model assumes that the daily air temperature always follows the sine curve described above and is not affected by cloud cover. Days with a relatively low maximum temperature are more likely to be cloudy than warmer days. This is modelled by regarding all days with a maximum temperature greater than a critical value for that month as being completely clear. If the maximum temperature is less than this value, there is a probability, appropriate to the month, that a given hour will be cloudy. The critical values and probabilities are shown in table 5.2, along with the resultant mean number of hours of sunshine per day and the number of clear days per month. These data from the model were compared with the number of clear days per month reported for Pt Augusta (South Australian Year book, 1974). Whyalla has about 3000 hours of sunshine per year, compared to the 2980 hours predicted by the model. The monthly distribution of hours of sunshine for Adelaide is shown for comparison (South Australian Year Book, 1974).

5.40 *The soil moisture submodel*

Soil moisture is an important determinant of plant growth and productivity, and it is considered by many to be the single most important variable. There has been a long history of agricultural indices emphasising soil moisture, or variables directly related to soil moisture. For example, in Australia, and especially South Australia, the precipitation: evaporation ratio (P/E) was applied in various forms, in an attempt to define agricultural zones (e.g. Prescott, 1934;

Prescott & Thomas, 1948). These indices used monthly mean values and their utility and extension was limited by the lack of facilities for handling large amounts of data. Computer models of soil moisture similar to that of Fitzpatrick, Slayter & Krishnan (1967), allow more detailed, probablistic statements to be made about the growing season, and allow more direct comparisons between meteorological events and plant response.

5.41 *Soil moisture budgets*

The modelling of soil moisture is essentially a matter of book-keeping. The equation is,

$$SM_{t+1} = SM_t + RF \pm RO - AE - DD \qquad \text{(E5.8)}$$

where SM_{t+1} & SM_t are the soil moisture at times t+1 & t, RF is the rainfall, RO is the runoff, AE is the actual evapotranspiration, and DD is the deep drainage (all units are mm). This equation must apply over any time period, but daily, 5 daily (pentad), or weekly models are the most common.

AE is usually calculated from the potential evapotranspiration, PE, and usually as a function of SP,

$$SP_t = (SM_t - WP) / (FC - WP) \qquad \text{(E5.9)}$$

where SP is the proportional (percentage) saturation, WP is the wilting point, and FC is the field capacity. There has been much dispute over the exact relationship between AE and PE, and it is clear from experimental results that the relationship varies greatly for different soils and vegetations. Baier (1968) reviewed these relationships. Stanhill (1964) argued that PE was of limited use in the arid zone since species varied so much in their response to water stress. The method of deriving RO and DD also varies, and in some cases both have been ignored.

5.42 *Types of soil moisture models*

No attempt is made in this section to summarize the many different soil moisture budget models proposed. Instead, examples of the main types are described. In section 5.47 two models, based on those of Baier (1966) and Fitzpatrick, et al. (1967) are described and tested against data for Wertigo.

The soil can be considered as one or more zones and the soil moisture modelled separately for each zone. The most obvious method is to define the zones according to depth, but the soil can also be zoned according to water availability as in the Fitzpatrick et al. (1967) model.

Holmes & Robertson (1959) proposed a "modulated soil moisture budget". In this model the soil was zoned by depth. During recharge the infiltrating rain first filled the uppermost zone, then the second, and so on. Any water remaining after filling the deepest zone being modelled was regarded as deep drainage. During evapotranspiration the uppermost zone was first dried to the wilting point, then the second, and so on.

Baier & Robertson (1966) proposed a "versatile soil moisture budget" which was an extension to the modulated budget. In Baier's model the recharge was as above, but evapotranspiration occurred from all zones simultaneously. The amounts taken from each depth was a function of the root density, the soil moisture storage (as SP), the potential evapotranspiration and its monthly mean. The equation was,

$$\text{(E5.10)} \qquad AE_t = \Sigma^n_{j=1} K_j * (SP_{j,\ t-1} / [FC_j - WP_j]) * Z_j * PE_t * \exp(-W * [PE_t - \overline{PE}]) \quad \text{for } j=1,2,\ldots,n \text{ zones.}$$

where Z was a function describing the relationship between AE & PE, K was a function accounting for root density, and W was a constant. McCowan (1971, 1973) described a model for tropical Queensland similar to that of Baier. This model included two zones corresponding to the two soil horizons in a duplex soil.

Fitzpatrick <u>et al</u>. (1967) published a model including two zones (or stores). In this case the "A store" corresponded to the soil moisture available to plants for evapotranspiration, while the "B store" was the soil moisture held by the soil at less than the wilting point. The recharge of the soil stores was more complicated than the depth zone models. After the rainfall had been corrected for runoff the water was apportioned to the A and B stores according to their storage capacities (in this case A : B = 3 : 1). Fitzpatrick <u>et al</u>. concisely described the process as follows:

> "From an initially dry condition (i.e., following exhaustion of both Store A and B, recharge is apportioned in the ratio 75% to Store A and 25%

> to Store B. If recharge occurs when Store A is exhausted but some storage remains in B, it is apportioned 3/1 between Store A and Store B, until B is refilled to its previous level. Store A is then refilled and any surplus apportioned 3/1 between Store A and Store B as before".

For the extraction of soil moisture, they used a function relating AE to PE and SP for water loss from store A. This was further modified by a function relating AE to the cumulative potential evapotranspiration since the initiation of the most recent growth period. A growth period began whenever the A store was recharged after being zero. If B was also zero, then somewhat more stringent conditions were needed to break the drought in that net rainfall (RF - RO) had to exceed 0.5 * PE for the pentad. Fitzpatrick et al. used this model to estimate the frequency of growth periods for several Northern Territory sites from the available climatic records.

Some relatively simple models have proved to be adequate in certain situations. Schreiber & Sutter (1972) used a soil moisture budget to determine growth period parameters for an Arizonan site. This model included a single soil store; runoff was related to rainfall, and actual evapotranspiration was assumed to be independent of soil moisture and dependent only on the date. Keig & McAlpine (1969) developed the WATBAL model for Australian conditions. Again a single store is used, and runoff and potential evapotranspiration are exogenous variables. A step function relates AE/PE to SP.

Such models are usually only valid for the locality for which they were derived. The WATBAL model was tested against the Wertigo soil moisture data and was found to be inadequate.

5.43 *Models used in other simulations*

It was mentioned in section 5.21 that some ecosystem models do not model rainfall and therefore cannot model soil moisture in any detail. These either take the approach that soil moisture is non limiting, (Van Dyne, 1969b), or that a definite growth season occurs (Walters & Bunnell, 1971).

Other ecosystem models include soil moisture models but these are usually only single zone models. There have been a number of different approaches to the estimation of the variables of the soil moisture budget equation. Armstrong (1971), and Vickery & Hedges (1972) treated potential evapotranspiration as an exogenous variable and related AE/PE to SM or SP. Van Dyne (1969a) calculated potential evapotranspiration from the mean temperature over 5 days and used a linear relationship between AE/PE and SM. Goodall (1969) calculated potential evapotranspiration from an exponential equation including SP. Runoff was related to rainfall by a quadratic equation.

Swartzman & Van Dyne (1972) used a two zone model, the zones corresponding to the rooting depths of grasses and shrubs. They regarded AE as proportional to PE and the water loss from each zone was dependent on the cover of grasses and shrubs.

5.44 *The Wertigo data*

Soil moisture data for Wertigo were made available by Dr R.T. Lange & Mr M. Willcox. Gravimetric soil moisture was recorded at 3 depths at 16 sampling dates spaced over 15 months. The data were recorded at 6 sites representing apparent vegetation, soil or topographic differences. One of these sites was chosen for the soil moisture model fitting since it was in uniform deep soil and had the longest record.

The field capactiy at this site was estimated by applying 100 mm of water to two areas of soil each approximately 4 m^2. The wet soil was covered with plastic to prevent evaporation and the plastic was dusted with dry soil. Four soil cores were taken 48 hr and 72 hr after the application of the water. After 48 hr the average % soil moisture in the top 30 cm of soil was 18.1 ± 0.5 (SE) by weight and after 72 hr was 17.7 ± 1.1% (SE) by weight. The bulk density was determined by carefully taking a core and determining its dry weight. The core volume was measured by back filling with a measured volume of fine dry sand. The average bulk density over 4 replicates for the top 30 cm of soil was 1.23 ± 0.05 (SE). This gave a volumetric field capacity of about 22%.

The variability of Wertigo soils was investigated in October 1973. Soil cores were taken at 5 depths down to 1 m at 29 sites, and soil moisture, Munsell colour, pH and presence of carbonate were determined. The soils proved to be very uniform, except for the water course near the dam, and shallower soils occurring on the ridge in the south west corner. The soil moisture distribution is shown in figure 5.17. Soil moistures were generally lower in wooded areas. It was eventually decided to treat the Wertigo soils as uniform, since the variation was apparently small, and further description of them would be time consuming.

5.450 *The soil moisture budget parameters*

This section discusses the method by which the soil moisture parameters were estimated in the Wertigo soil moisture model. The main parameters are; RF, RO, and AE. Deep drainage is accounted for in the model itself. The initial soil moisture may be handled by choosing an arbitrary value (e.g. all stores at the wilting point) and then running the model for a period of more than 12 months. The soil moisture values after this time appear to be almost independent of the initial value.

5.451 *Rainfall*

Daily rainfall figures wereavailable from Middleback homestead (see section 5.22), and a rain gauge at the site was used to measure the total amount of rain between soil moisture readings. The data in table 5.3 indicate that there were no major differences in rainfall at the Wertigo site and at Middleback homestead.

5.452 *Runoff*

There has been little investigation of runoff in the Australian arid zone. Keller (1906) proposed that,

(E5.11) $RO = 0.94 * RF - 16.0$ ... ins

for monthly runoff in German river catchments. This form of equation has been applied by other workers to small experimental plots. Schreiber and Kincaid (1967) found that,

$$\text{(E5.12)} \qquad RO = a + b * RF$$

was as good as other runoff predictors which included such variables as rainfall intensity, previous soil moisture, and crown spread. Kohler & Richards (1962) included soil moisture in a runoff equation. They used,

$$\text{(E5.13)} \qquad RO = (RF^n - d^n)^{1/n} - d$$

where $n = c + k * d$, c & k are constants, and d is the moisture deficiency, i.e. (FC - SM). A widely used equation is that of the U.S. Soil Conservation Service (Branson et al., 1972). For rangelands soils they proposed,

$$\text{(E5.14)} \qquad RO = (RF - 0.2 * d)^2 / (RF + 0.8 * d)$$

where d is as above.

Fitzpatrick et al. (1967) used a relationship which is presumably the same as that described by Slatyer (1968) as a modification of a relationship derived by Blaney & Criddle (1957) for West Pakistan. It applies to runoff and rainfall measured over pentads (5 day units), and it was initially used in the Wertigo soil moisture model, but was later replaced by the U.S. Soil Conservation Service equation.

Jackson (1958) described the hydrology of the soils of Yudnapinna St., 100 km north of Wertigo. His data could form the basis of a more detailed runoff-infiltration model.

5.453 *Evaporation*

Evaporation is of fundamental importance in many aspects of agricultural and pastoral management, yet it is only rarely recorded at Meteorological Stations. In Australia the only data collected with a reasonable coverage, besides rainfall, are daily maximum and minimum temperatures. Therefore a relationship of the form

$$PE = f(TE_{max}, TE_{min}) \qquad \text{(E5.15)}$$

where TE_{max} and TE_{min} are the daily maximum and minimum temperatures, is most needed. Equations, such as that of Penman (1948), require meteorological variables rarely available in most parts of the world. A number of empirical equations have been proposed (e.g. Prescott, 1938; Thornthwaite, 1948). These relationships usually apply to evaporation over periods of up to one month and use mean monthly temperatures and humidities. Caution is needed in applying these equations to time periods different to those for which they were derived. Many of these equations are of form such that,

$$(f[x_1] + f[x_2] + \ldots + f[x_n]) / n \neq f([x_1 + x_2 + \ldots + x_n]/n) \qquad \text{(E5.16)}$$

and therefore errors will be introduced when different time periods are used. An empirical relationship must be reassessed when it is applied to either a different locality or to a different time period.

Evaporation takes place when the vapour pressure of the air is lower than the vapour pressure at the water surface. This principle is expressed by Dalton's law,

$$\text{(E5.17)} \qquad PE = C * (e_0 - e_a)$$

where e_0 is the vapour pressure (VP) at the evaporating surface, e_a is the VP of the air above the surface, and C is a coefficient dependent on wind velocity and possibly other factors. The equation is difficult to apply since e_0 can rarely be determined directly and e_a, derivable from humidity data is rarely recorded in the arid zone.

One of the simplest equations for potential evapotranspiration (PE) is that of Papadakis (1966),

$$\text{(E5.18)} \qquad PE = 0.5625 * (e_{TE_{max}} - e_{TE_{min}-2}) \quad \ldots \text{ cm month}^{-1}$$

where $e_{TE_{max}}$, the saturated VP (mb) at the maximum day temperature is used to estimate e_0, and $e_{TE_{min}-2}$, the saturated VP at 2°C less than the minimum temperature is used to estimate e_a. (TE_{min} -2) is an estimate of the dew point and the saturated vapour pressure at the dew point is equal to the vapour pressure of the air. The equation was derived for PE in cm month^{-1} and for mean monthly temperatures. Papadakis used the constant, 0.5625, for PE throughout the year and for all climates. It was tested for Australian arid zone sites with data published in the Bureau of Meteorology, Monthly, Climate Data (1970+) and was found to give a poor fit.

Fitzpatrick (1963) proposed an equation relating Australian Standard Tank evaporation (EV) to monthly mean maximum daily temperature, dew point temperature and day length. It is of the form,

(E5.19) $$EV = a + b * (e_\theta - e_d)$$

where, a & b are constants, e_d is the saturated VP at the dew point, and e_θ is the saturated VP at a synthetic temperature. Fitzpatrick found empirically that,

(E5.20) $$\theta = k * TE_{max} * (1 + \log[N / 12])$$

where, N is the day length in hours, and TE_{max} is the maximum daily temperature, gave a good linear relationship between $(e_\theta - e_d)$ and mean monthly pan evaporation. For most inland localities k was constant and equal to 0.9.

Fitzpatrick demonstrated that the synthetic temperature was better correlated with pan evaporation than were other common estimators. From individual monthly mean temperatures, Fitzpatrick derived the equation for the mean daily evaporation in a given month;

(E5.21) $$EV_{day} = 0.036 + 0.359 * (e_\theta - e_d) \quad \ldots \text{ ins day}^{-1}$$

for VP in inches of mercury, which is equivalent to;

(E5.22) $$EV_{day} = 0.91 + 0.27 * (e_{\theta} - e_{d}) \quad \ldots \text{ mm day}^{-1}$$

for VP in mb. This equation is not directly applicable to calculating daily evaporation from daily maximum temperature, dew point and day length, since the Fitzpatrick equation is of the form of equation 5.16.

The use of the Fitzpatrick equation requires that the dew point temperatures are available. Dew point is often recorded and can also be calculated from the humidity, but in many cases neither are available. Papadakis (1966) used (TE_{min} -2) to estimate dew point, and this was tested for Australian conditions by gathering monthly mean dew point data for 11 arid zone sites for two years from the Bureau of Meteorology, Monthly Climate Data (1970+).

As can be seen in figure 5.9 there was a large amount of scatter in the pooled data, although this was less in the case of individual sites. (TE_{min} -2) was a poor estimator of dew point in most cases. A quadratic equation was fitted to the pooled data and the result was,

(E5.23) $$d = 4.15 + 0.0617 * TE_{min} + 0.0135 * TE^{2}_{min} \quad \ldots {}^{o}C$$

This equation should only be used when local relationships were not available.

The relationship between Class A pan evaporation (the most widely accepted standard), Australian Standard Tank evaporation, Penman's PE and other evaporation estimates has been investigated by Hounam (1965). Again there was much variation between sites. However, since most soil moisture budgets are fitted interatively, any accurate predictor of evaporative loss would be a suitable estimator of PE. The differences between PE estimators would be accounted for in the fitted AE/PE function.

At present no suitable relationship between evaporation and commonly available meteorological variables appears to be available. The best predictors require the saturation deficit, or an approximation of it, which implies that dew points are needed. Most empirical predictors have been derived for monthly data and need to be reassessed before they are used to estimate daily evaporation.

It was therefore decided to use published mean monthly Class A pan evaporation data (Australian Water Resources Council, 1968) to estimate the evaporation at Wertigo. The daily evaporation was assumed to be constant throughout each month, and was set to $^{1}/_{30}$ or $^{1}/_{31}$ etc., of the mean monthly evaporation. This was used for the fitting of the soil moisture models described below. The programs were written such that a suitable function could be inserted if available. The potential evapotranspiration was estimated as 0.8 times the Class A pan evaporation (McCowan, 1973).

5.454 *Evaporation rates in the grazing model*

The mean monthly evaporation data is not suitable for use in the grazing model, where the other climatic variables are all simulated and, therefore, available for estimating evaporation rates. It is important to correlate periods of high or low temperature with higher or lower evaporation rates, so that the soil moisture budget acts realistically to heat waves or cool weather.

It was decided to use a simple empirical function to calculate the evaporation rate from daily maximum temperature. The function was of a form such that there was no inequality as discussed in equation 5.16, and it was fitted to mean monthly evaporation rates for Whyalla and mean monthly maximum temperatures, as estimated by the temperature model (section 5.3).

A function of the form,

$$EV = a + b * TE \tag{E5.24}$$

was tried, but this clearly showed the temperature lagged behind the evaporation rate. This is not unexpected, since Prescott (1942) showed that temperature lagged behind solar radiation input in Australian arid areas, and many authors have demonstrated the importance of solar radiation in the evaporation process. I sought to overcome this by including the number of the month in the year, M, i.e. January=1, to December=12, in a function,

$$EV = a + b * TE + c * M. \tag{E5.25}$$

This showed an improved fit, but an even better fit was obtained by using the mean day length for each month rather than the number of the month. The equation, (E5.26) $$EV = -6.62 + 0.125 * TE + 0.654 * DL \quad \ldots \text{ mm day}^{-1}$$

where TE is the maximum day temperature ($^{\circ}C$) and DL is the mean day length in hours, is used in the model (fig. 5.10).

This function could be replaced with a more complex one (e.g. Penman's), since variables such as air temperature, solar radiation and wind velocity are available in the complete grazing model. It is not included in the present version because there is insufficient validation data to warrant the more detailed treatment.

5.460 *The Wertigo soil moisture model*

The next two sections describe the testing of two different models, and adaptions of them, against the Wertigo soil moisture data.

5.461 *The "Fitzpatrick model"*

A program was written to simulate soil moisture according to the model of Fitzpatrick et al. (1967)(section 5.42). Runoff and potential evapotranspiration were estimated as described above. The program was written such that a range of A store and B store values could be tested for any set of AE/PE functions and growth function, since it was expected that these would differ from the Alice Springs soil functions.

The program could be run either interactively or under batch processing.

The soil moisture at the Wertigo site was estimated by a summation technique as shown in figure 5.11. The summed error (i.e. [simulated - observed]) and the summed squared error (i.e. $[\text{simulated - observed}]^2$) were printed for each set of parameters tested (see fig. 5.12). James (1972) discussed parameter estimation by hydrological models. He pointed out that trial and error fitting was an acceptable method if the parameter values were being estimated for the purpose of simulating occurrences at a single site. The method is unacceptable if attempts were to be made to correlate the estimated parameters with other parameters, or if parameters for different sites were to be compared. James described a method of iterative fitting of 6 parameters in a commonly used hydrological model. He found that the "steepest ascent" methods of parameter correction "bogged down" on rough response surfaces and took too much time in estimating the slopes. He therefore used a trial and error approach to parameter correction, based on the user's "qualitative feel" for the system. The same approach was used in this model.

The growth function produced misleading results in the Wertigo model, and it was found that it was better replaced by a constant. The result was not unexpected since the Fitzpatrick model was derived for perennial grasslands whereas in Wertigo perennial bush is dominant, with ephemeral grass and herb inputs. The site used for the initial calibrations supported a small quantity of ephemerals only a few times during the 16 month data collection period.

It was found that for a range of A and B stores and AE/PE functions, the best fit occurred with a total store, (i.e. field capacity) of about 22%, which was in good agreement with the measured field capacity. The summed squared error was 872 and this occurred when the A store was 10% by volume and the B store 12%. A comparison of the observed data and the predicted soil moisture data indicated that the runoff section of the model was under-estimating runoff. No attempt was made to improve this function in this model, but it is discussed again, below.

5.462 *The "Versatile Budget" model*

The second model tested was that of Baier & Robertson (1969). The soil moistures in each of the zones, 0-10 cm, 10-35 cm and 35-60 cm were estimated as shown in figure 5.11. The program was written to allow the Z and K parameters of the actual evapotranspiration equation (eq. 5.10) to be adjusted. The exp(-w * [PE_i - $\overline{PE}$]) term of the equation was omitted since $\overline{PE}$ was being used to estimate PE_i and the term reduced to being equal to one. The runoff was initially calculated as in the Fitzpatrick model. The program printed the summed error and summed squared error for a range of different field capacities for each set of Z and K parameters, and again it could be run either interactively or under batch processing.

No attempt was made to measure the change of root density with depth in order to establish the K parameters. It was realised that in the Australian arid much of the evaporative loss occurs via soil evaporation. Hence effective root density would not necessarily be similar to actual root density. The Z parameter was based on the ratio of SM/FC rather than on SP as in the versatile budget. This was included to allow the SM to fall below the apparent wilting point, as observed in the field.

The best fit was obtained with the Z and K parameters as shown in figure 5.13, and again for a field capacity of 22% by volume. The summed squared error was 1543 for the three zones. This was a better fit than the Fitzpatrick model, but two errors were still apparent. First, the model predicted an influx of water into the second zone in June 1972 when none was recorded, and again in February 1973 the model predicted an influx of water into the third zone when none was recorded. In June 1972 there had been no heavy falls but instead a series of light falls which the model erroneously predicted would gradually fill the soil stores. This implied that existing soil moisture, as well as the amount of rain, must affect runoff. The second error was most obvious in February 1973. The predicted soil moisture for both the first and second zone fell more rapidly than the measured values. This was probably due to the true potential evapotranspiration, during the exceptionally wet season, being lower than the estimate used (i.e. the mean February evapotranspiration).

The model was re-run, this time with the U.S. Soil Conservation Service runoff equation (section 5.452) in place of the Fitzpatrick et al. (1967) equation. This gave an improved fit and a summed squared error of 1336 for a field capacity of 23% by volume. The Z and K parameters remained as shown in figure 5.13, and the details of the fit are shown in figure 5.14. The model still under estimated runoff but some improvement had been made.

5.47 *Discussion*

The versatile budget model gave the best fit to the recorded data. It is more useful in ecosystem simulation models since it predicts soil moisture in three zones, thereby supplying more information to the plant growth model. It also requires less computing time and memory. The results indicated that the runoff function requires more investigation and for Wertigo the function is probably of the form,

$$RO = f(SM, RF) \qquad \text{(E5.27)}$$

The length of the record for Wertigo was too short for any further conclusions to be drawn from these data. It is also clear that the mean monthly evaporation is a sufficient, but imperfect, basis for estimating evapotranspiration.

The versatile budget model was included in the final model. The soil moisture was estimated for each of the 37 cells, assuming that the rainfall and evapotranspiration were uniform across the paddock. The runoff from each of the cells was calculated by the U.S. Soil Conservation Service equation. However the RF term included both the rainfall, plus any run-on from other cells. The soil moisture budgets for the cells were calculated in an order such that the total run-on for each cell was known before the calculations for the cell were performed. The runoff directions used for Wertigo are shown in figure 5.15.

5.5 *The wind model*

Winds are one of the most studied of all the meteorological parameters because of their close association with the major atmospheric pressure systems. Many studies have described and analysed the annual variation of the pressure systems, their resultant wind patterns, and their effects on such events as rainfall. Karelsky (1961) and Grentilli (1971) have described the progression of cyclonic and anticyclonic pressure variations and the related wind systems across Australia. Although several attempts have been made to build models of the global atmosphere dynamics (e.g. GARP, see Bolin, 1974 for a general review), these are of little value in modelling day to day wind patterns at a particular site.

The wind model is based instead on the data presented by Brookfield (1970). She studied the wind patterns in Central Australia with special emphasis on their erosional properties and sand dune movements. The most southerly site for which she presents data is Oodnadatta (600 km N.N.W. of Whyalla), for which she includes wind direction for two speed classes and for 4 seasons. This data was used to build up a table of probabilities for each of the four seasons. The classes represented, calm conditions, and wind from 8 compass points with a speed of either greater than or less than 9 knots (4.6 m s^{-1}). The model was written to choose a wind at random, from the distribution for the appropriate season (fig. 5.16). The actual wind speed was then calculated by assuming it was distributed uniformly at random between 0 and 4.6 m s^{-1}, or 4.6 and 9.2 m s^{-1}.

The model assumes that the wind speed and direction are constant throughout the day. This introduces errors into the model since Wertigo experiences sea breezes from the southeast in the warmer months, as well as the normal daily variations in wind velocity. Nor does the model assume any correlation between successive days. This is a major fault, but the detailed model called for would require enormous amounts of data, e.g. hourly wind velocities over many years. Even if this data had been available in a computer compatable form, the analysis would be well beyond the scope of this thesis.

A Markovian approach would appear to be a promising method, due to the dependency of the wind velocity on the progression of fronts. This would be further complicated by local effects such as sea breezes, and more rarely the intrusion of the northerly tropical wind patterns.

Fig. 5.1. The monthly rainfall distribution as observed at Middleback and as predicted by the two main models.

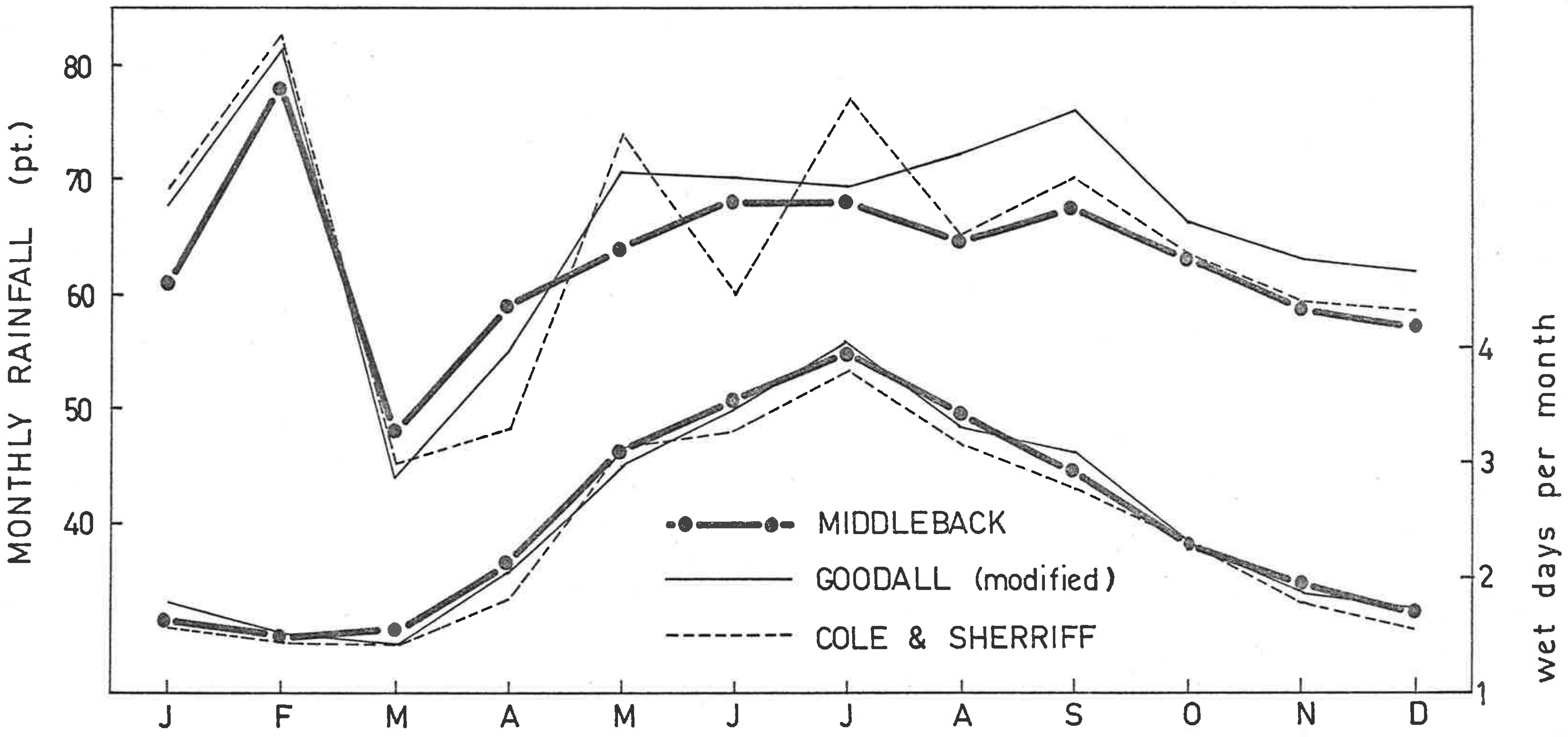

Fig. 5.1. The monthly rainfall distribution as observed at Middleback and as predicted by the two main models.

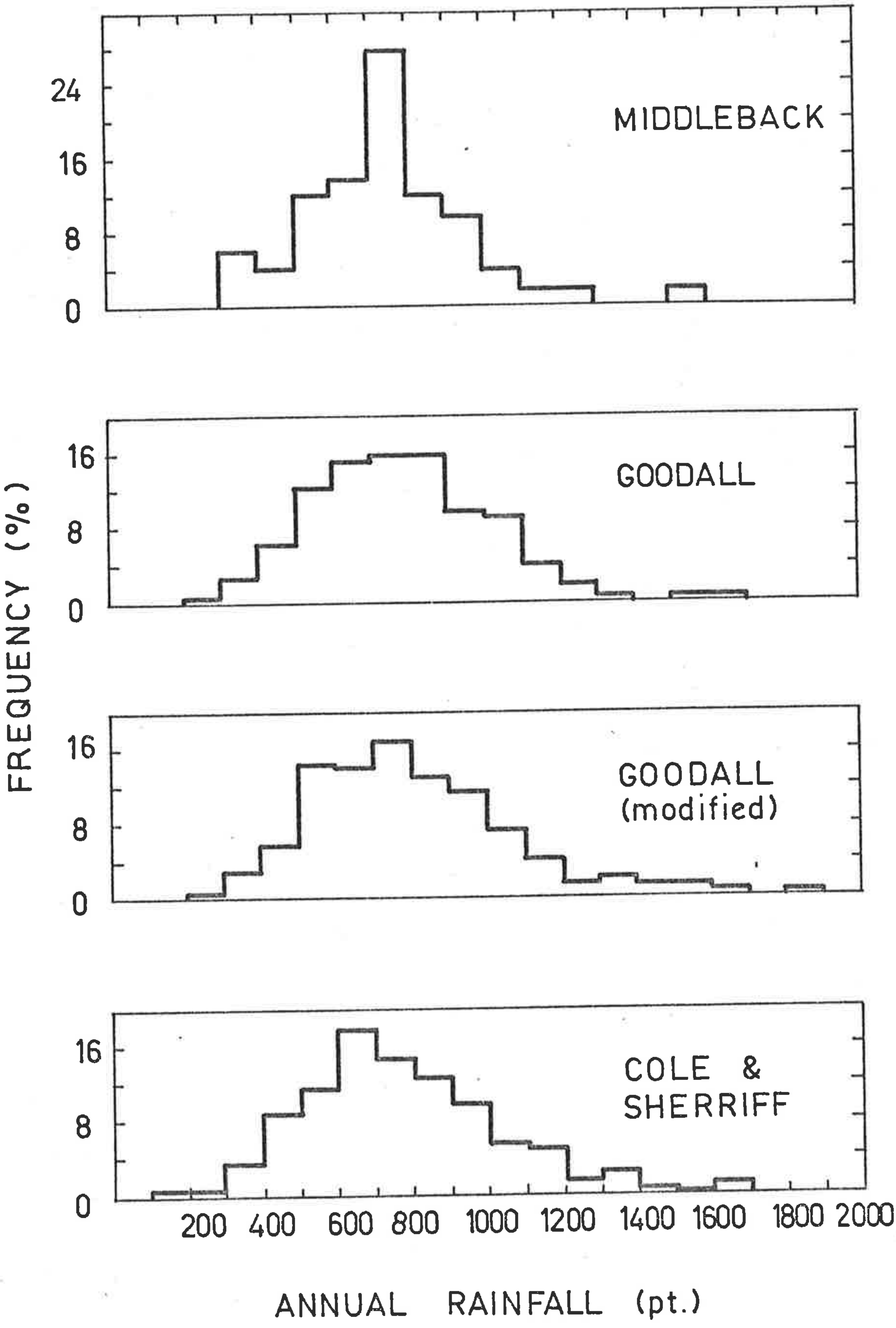

Fig. 5.2. The frequency distribution of annual rainfall as observed at Middleback and as predicted in the rainfall models.

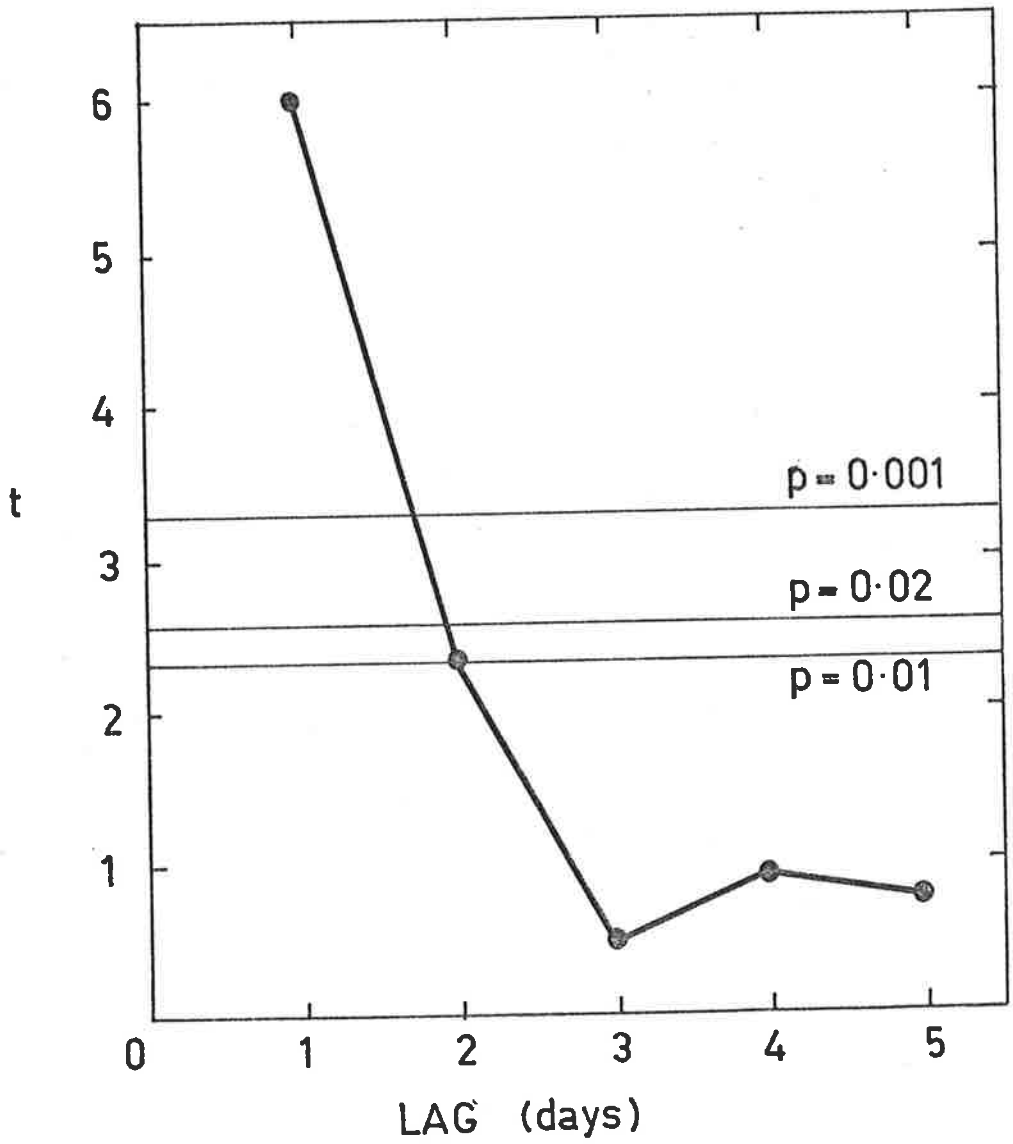

Fig. 5.3. The results of the Wald-Wolfowitz test for correlation between daily rainfall. The results are expressed as "Student's t" values with 47 degrees of freedom.

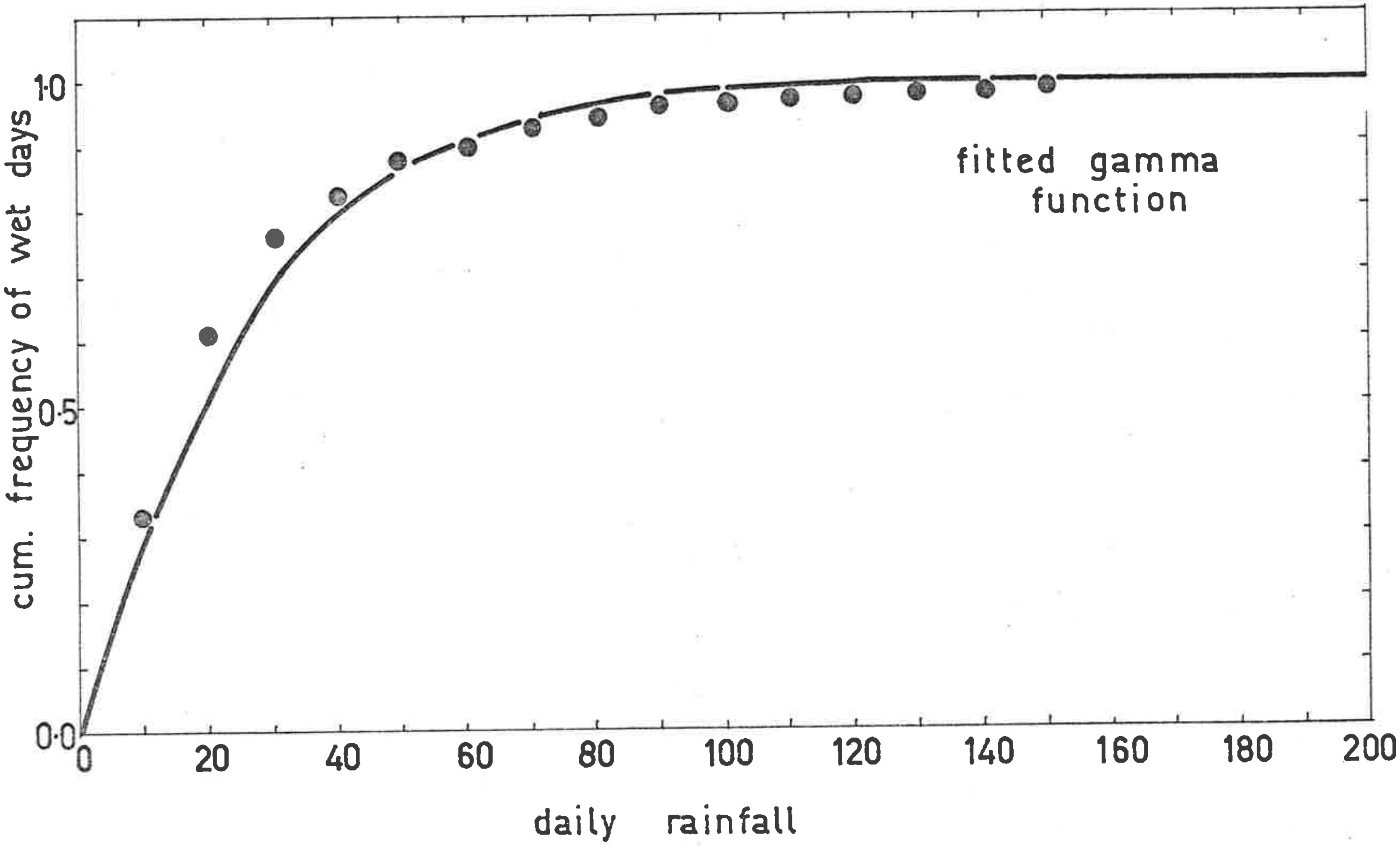

Fig. 5.4. The gamma function fitted to the cumulative frequency of daily rainfall amounts recorded at Middleback.

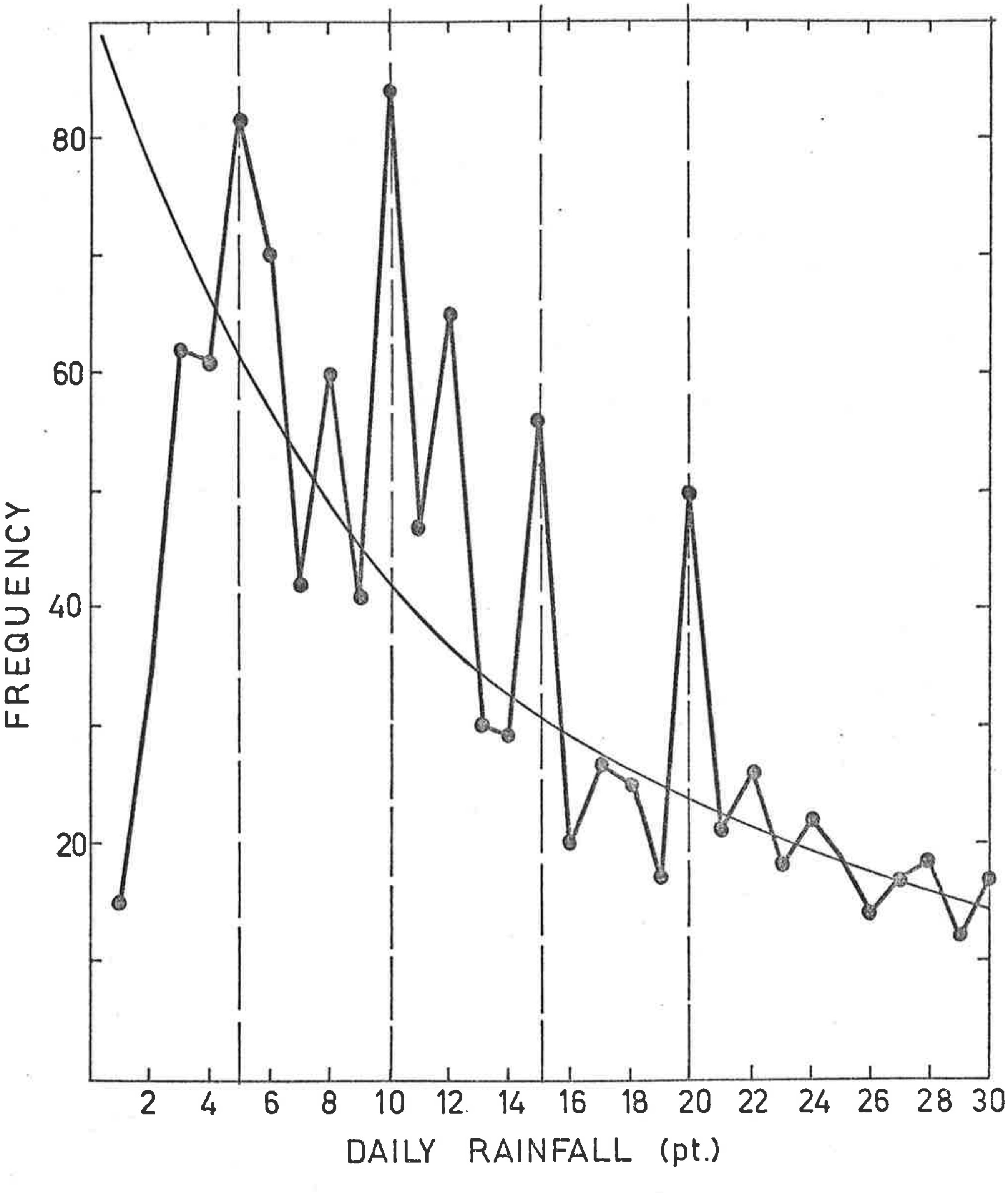

Fig. 5.5. The frequency in 48 years of daily rainfall amounts recorded at Middleback for rainfall amounts of up to 30 pt. The smooth curve was fitted by eye.

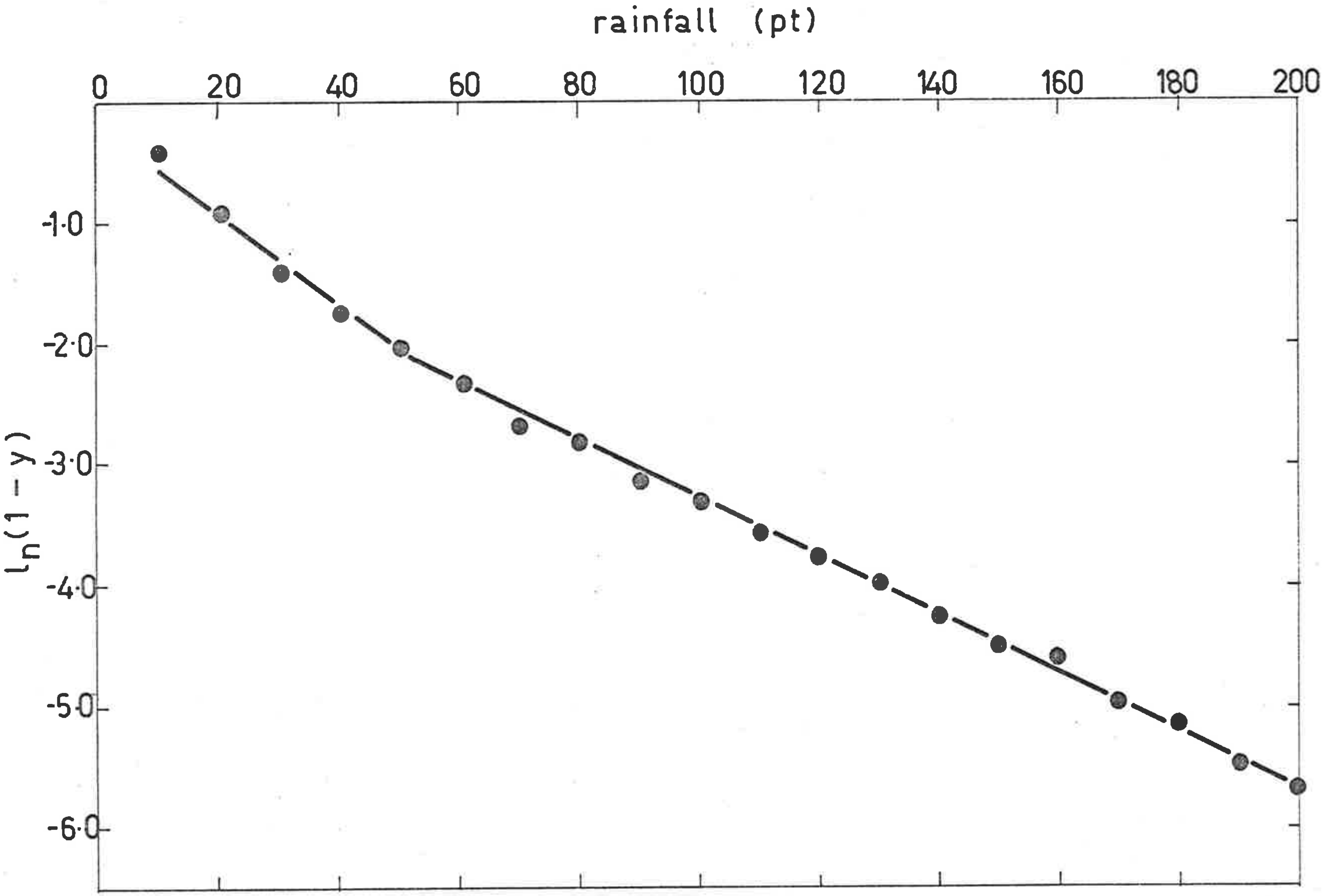

Fig. 5.6. The fitting of the simplified daily rainfall distribution function, $y = 1 - \exp(- C * x)$, where y is the cumulative frequency of daily rainfall amounts and x is the rainfall amount. The parameter c was estimated from the slope of the line for the intervals $20 < x < 49$ pt and $x > 50$ pt.

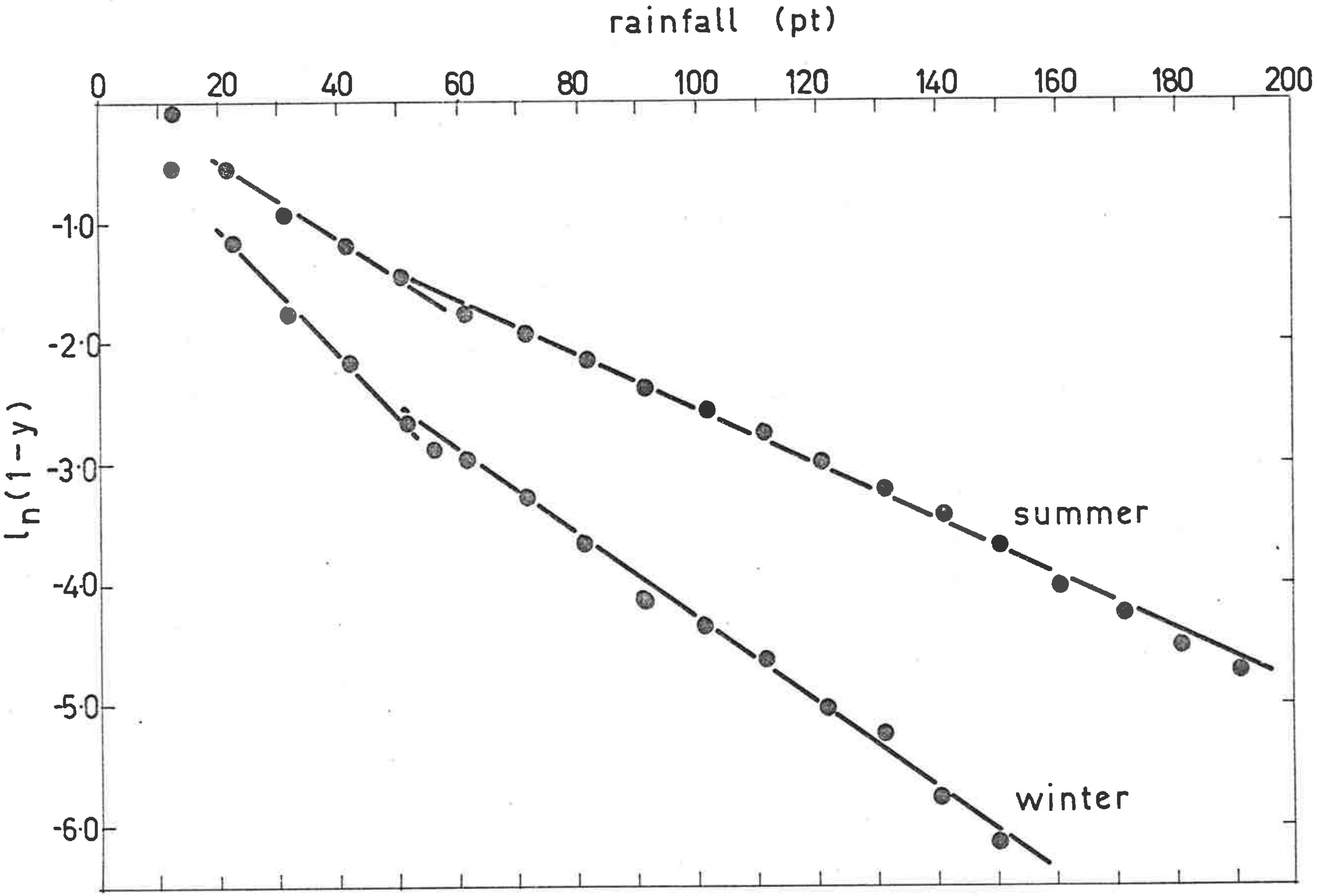

Fig. 5.7. Similar to fig. 5.6. except that summer and winter rainfall data have been separated.

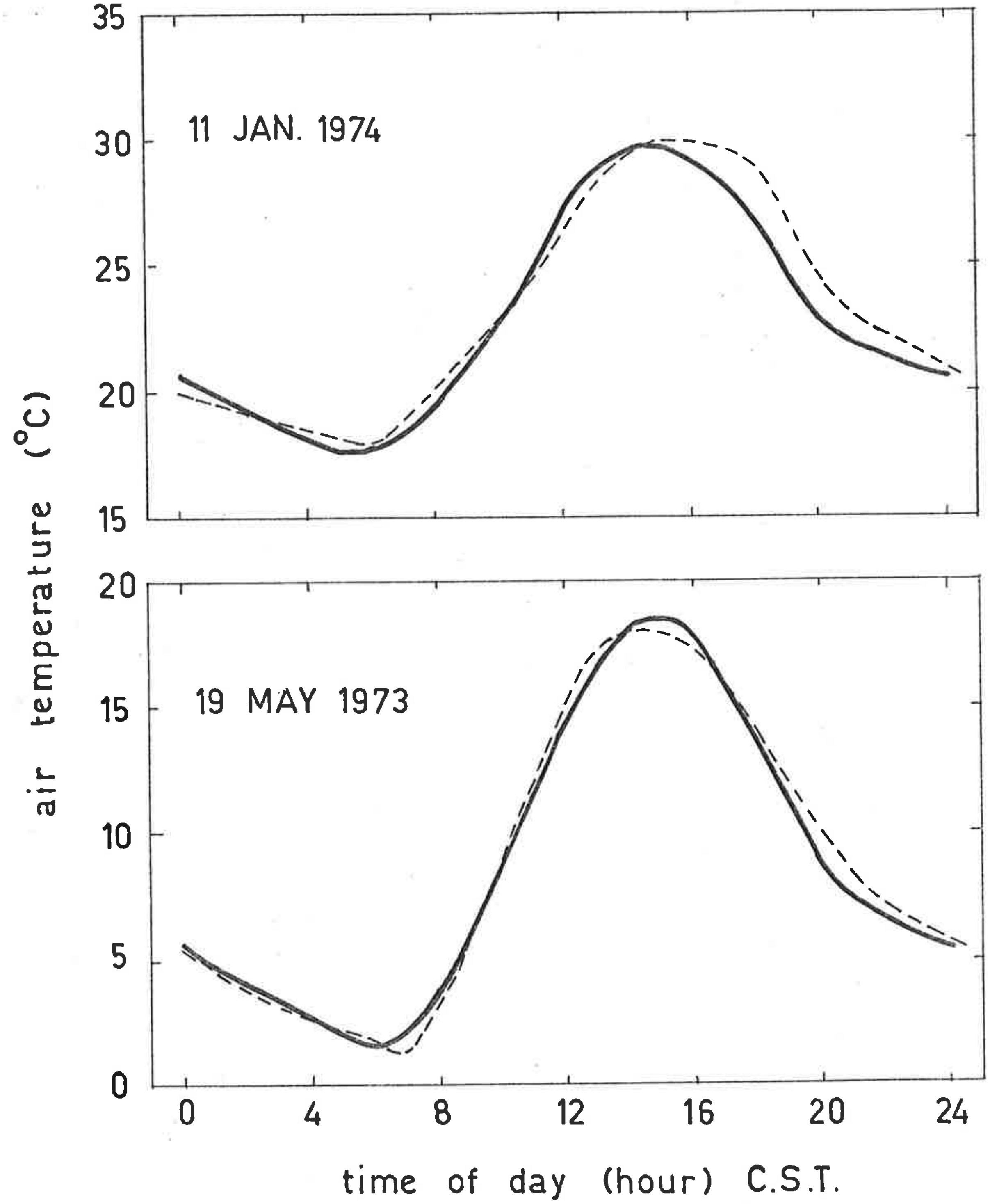

Fig. 5.8. A comparison of the recorded (dashed line) and simulated hourly temperatures (solid line) on two days at Middleback. The days were selected to be clear of cloud, and the simulated temperatures were adjusted to have the same minimum and range as the recorded temperatures.

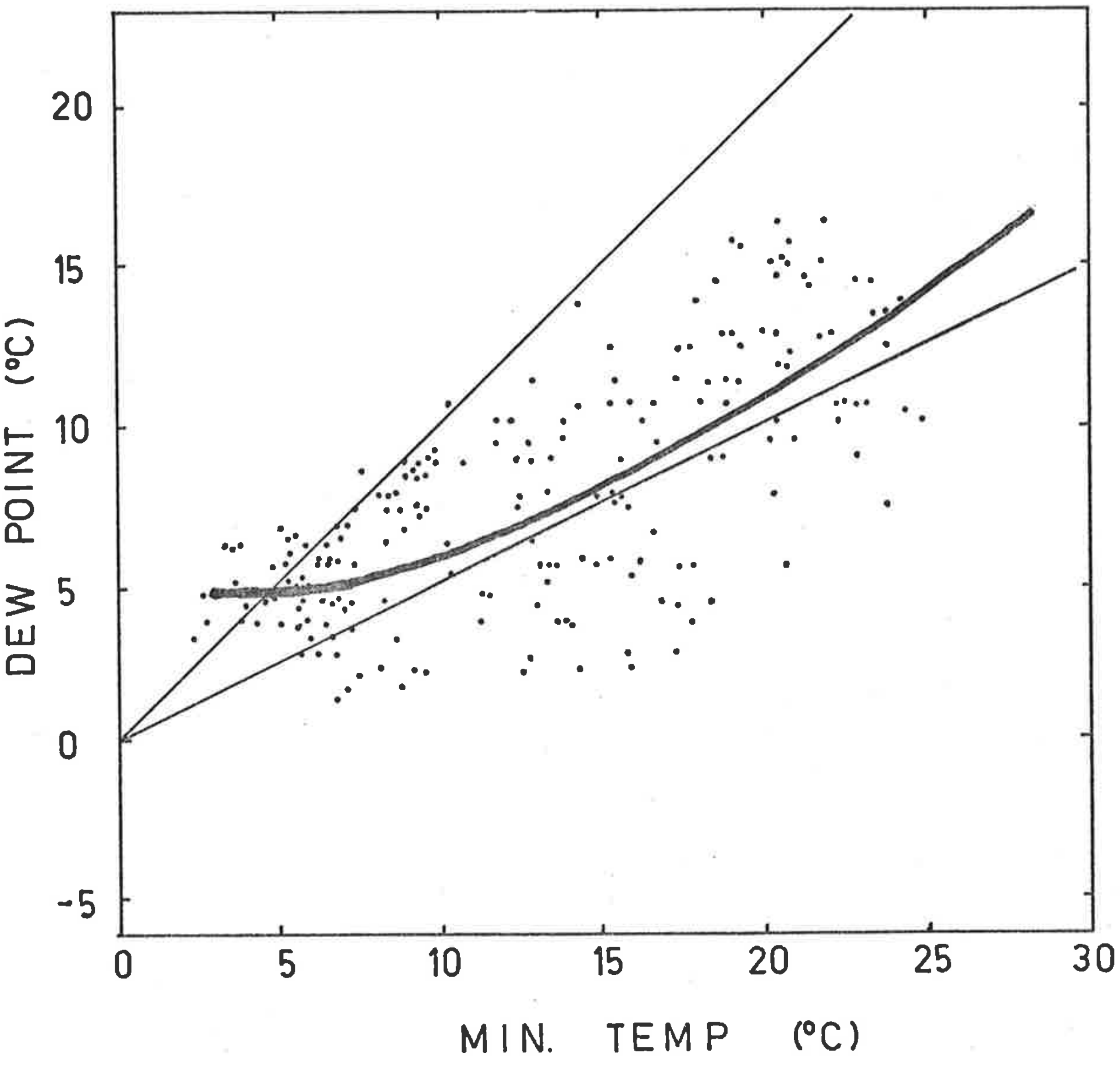

Fig. 5.9. Monthly dew point data compared with monthly mean minimum temperatures for 11 arid zone sites over 2 years. The fitted function (solid line) is,

$$d = 4.15 + 0.0617 * TE_{min} + 0.0135 * TE_{min}^2$$

The other lines represent, $d = TE_{min}$ and $d = 0.5 * TE_{min}$.

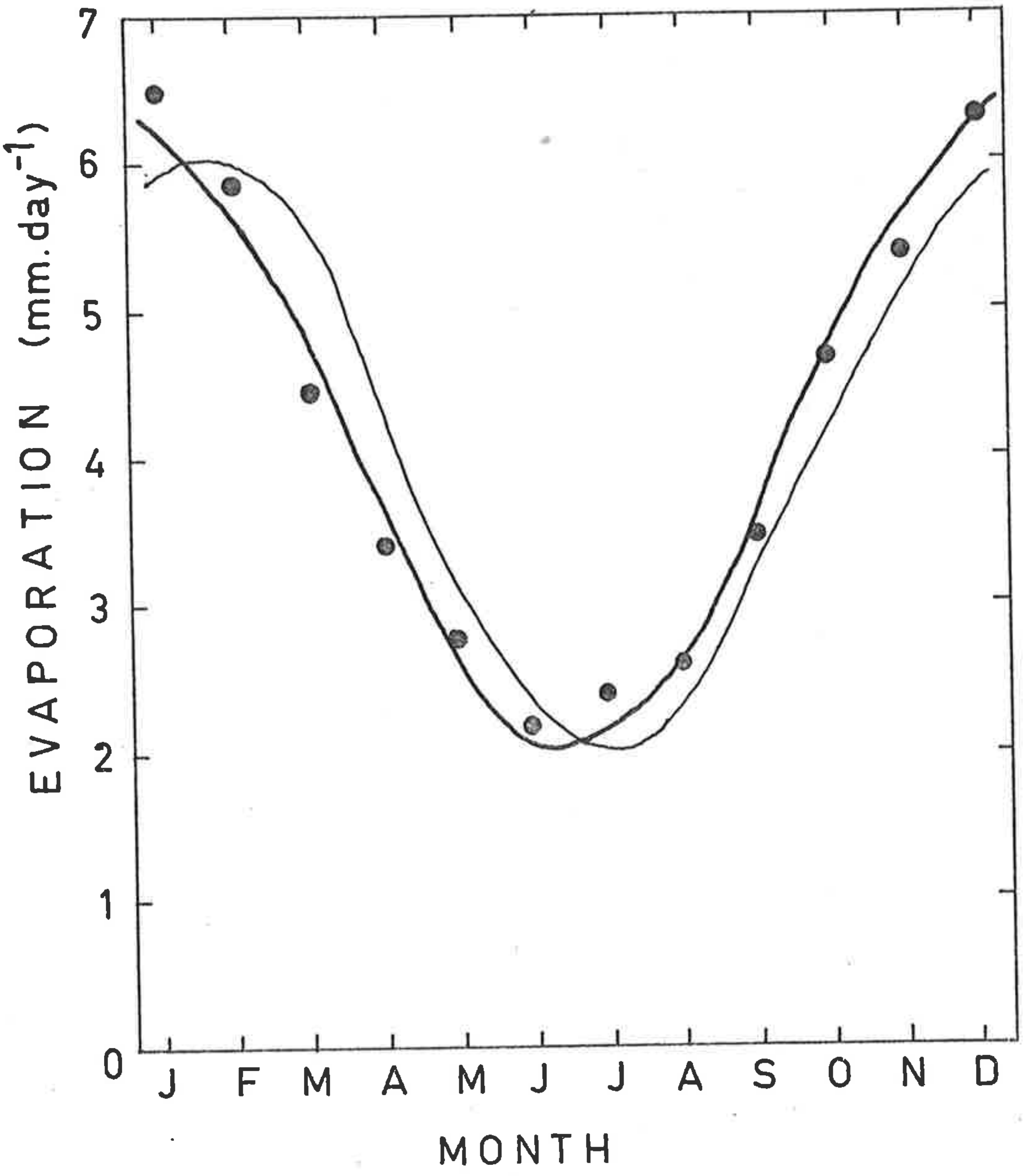

Fig. 5.10. A comparison of the monthly evaporation at Whyalla (●) and the equations, EV = 3.34 + 0.326 * TE (thinner solid line), and EV = - 6.62 + 0.125 * TE + 0.654 * DL (thicker solid line).

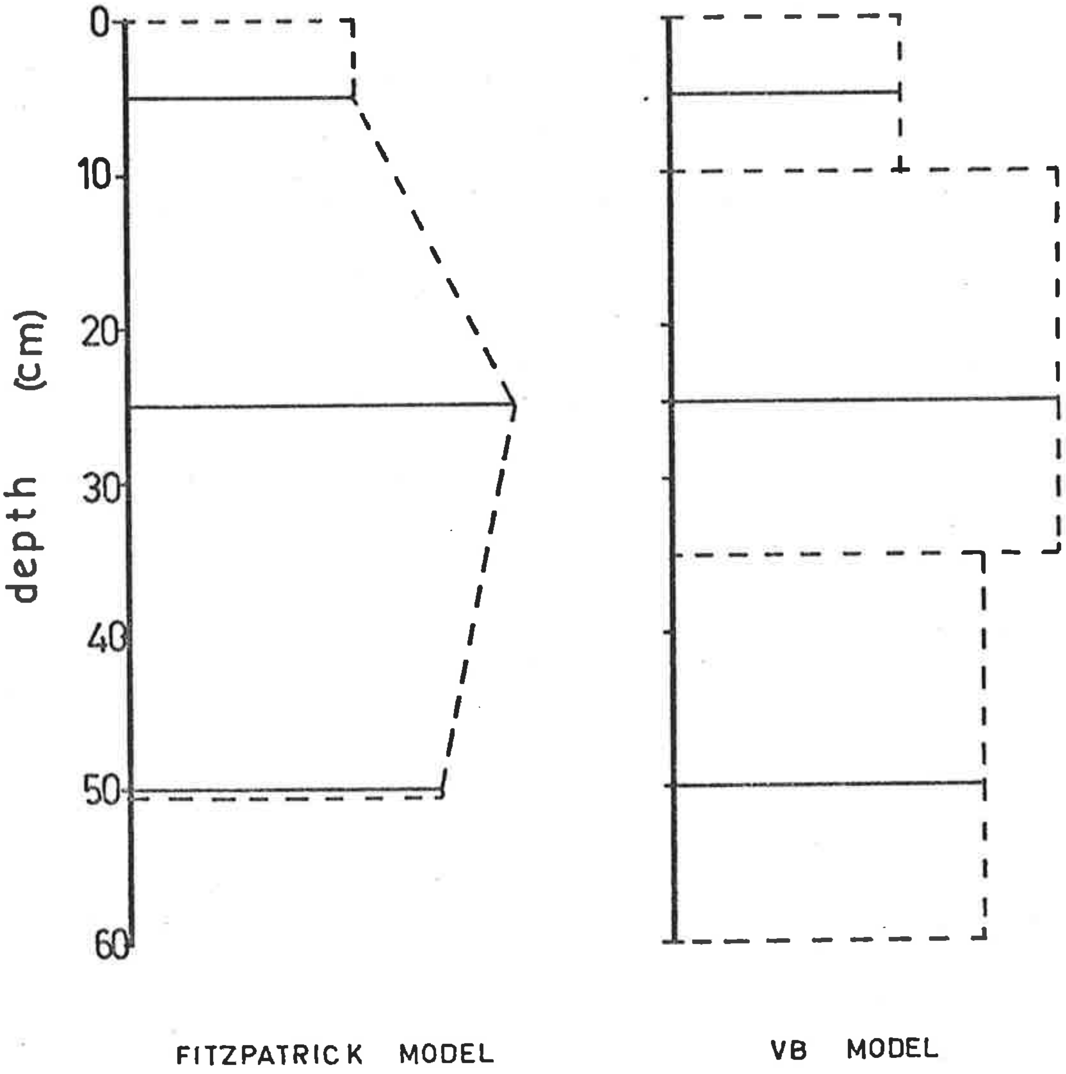

Fig. 5.11. The method of calculating the soil moisture values to be used in fitting the models, from the field measurements. The solid horizontal lines represent the measured soil moisture, and the total soil moisture is the area included in the dotted lines.

```
NAMELIST/X/ REQUEST.
        $X Z=5*.05,.1,.25,.4,.6,.8,AK=.7,.2,.1,7*0. $
 BEST FIT IS 1094.1 ON AX= .24
  PUNCH ANY CHAR IF WANT MORE LISTING, BLANK IF NOT


NAMELIST/X/ REQUEST.
        $X Z=5*.01,.1,.25,.4,.6;.8 $
 BEST FIT IS 1089.7 ON AX= .24
  PUNCH ANY CHAR IF WANT MORE LISTING, BLANK IF NOT
       YES
 AX        .10    .12    .14    .16    .18    .20    .22    .24    .26
 DEV   757.0 637.2 519.0 394.0 269.6 143.5  27.4 -82.0-193.2
S DEV    14714 10825  7609   4966  3107   1973   1438   1090   1524
DEV 1      151   124   104     83    63     41     19     -8    -40
DEV 2      342   300   253    202   152    102     54      0    -52
DEV 3      264   213   161    108    55      0    -46    -74   -102
S-D 1     1639  1142   839    594   423    289    210    147    247
S-D 2     8606  6675  4916   3333  2112   1193    623    388    511
S-D 3     4468  3007  1854   1039   573    491    605    555    767
 IF YOU WANT THE DAILY DATA, PUNCH ANY CHAR.
       YES


  BEST FIT FOR AX= .24
 DAY TOT-SM T-EV   RF   SM ZONE 1 2 3   RECORDS  ZONE 1 2 3
*  97   78.9    .2   0.0   8.7  33.8  36.4   8.0  31.0  32.0
* 160   74.2    .1   0.0   8.9  30.7  34.6   7.0  28.0  28.0
* 187   74.6    .0   0.0  10.2  30.1  34.3  11.0  29.0  29.0
* 216   76.8    .2   0.0  13.0  30.0  33.9  16.0  31.0  29.0
* 234   87.0    .6   0.0  18.4  35.0  33.5  16.0  27.0  32.0
* 264   78.2    .1   0.0  11.8  33.6  32.8   9.0  32.0  31.0
* 291   79.7   1.3   0.0  16.3  31.6  31.8  17.0  30.0  29.0
* 319   73.7    .4   0.0  13.3  29.9  30.5   8.0  29.0  26.0
* 347   69.7    .1   0.0  10.2  29.6  30.0   6.0  30.0  32.0
* 376   70.5    .1   0.0  11.5  29.2  29.8   7.0  28.0  29.0
* 411  108.8   1.4   0.0  12.8  51.9  44.1  19.0  55.0  31.0
* 425   96.2    .7   0.0  11.6  43.5  41.1  13.0  52.0  30.0
* 438   89.9    .4   0.0  11.1  39.4  39.4  12.0  53.0  33.0
* 452   84.0    .3   0.0  10.6  35.8  37.6   9.0  35.0  31.0
* 515   86.4    .3   0.0  13.2  38.5  34.8  16.0  33.0  31.0
* 543  108.3    .7   0.0  20.7  53.2  34.4  20.0  53.0  32.0
NAMELIST/X/ REQUEST.
        $X NA=%5,Z=.01,.02,.03,.04,.05,.1,.25,.4,.6,.8 $
 BEST FIT IS 1045.8 ON AX= .24
  PUNCH ANY CHAR IF WANT MORE LISTING, BLANK IF NOT
```

Fig. 5.12. The output from the interactive version of the 'versatile budget' model used in fitting the model to the Wertigo data. The NAMELIST requests allow changes to the parameters of the model. The model is then run for 550 days with a number of different field capacity values (10 to 26% in the above example). The best fit (smallest sum squared deviation for the 3 depths over the 16 readings) is then printed, and more output may be requested if it is wanted.

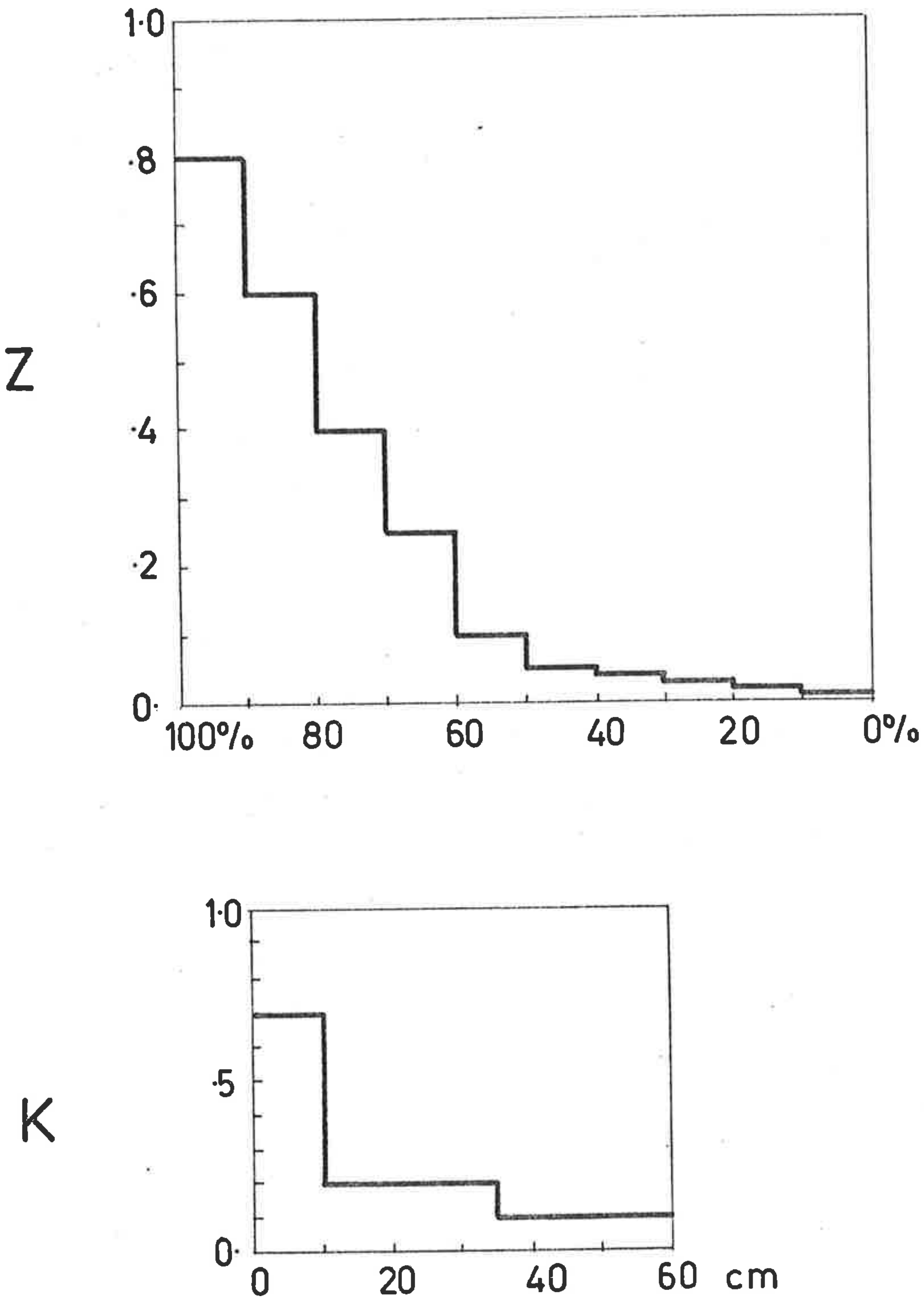

Fig. 5.13. The best fit for the Z and K parameters in the VB soil moisture model. Z is plotted against the ratio SM/FC, while K is plotted against depth.

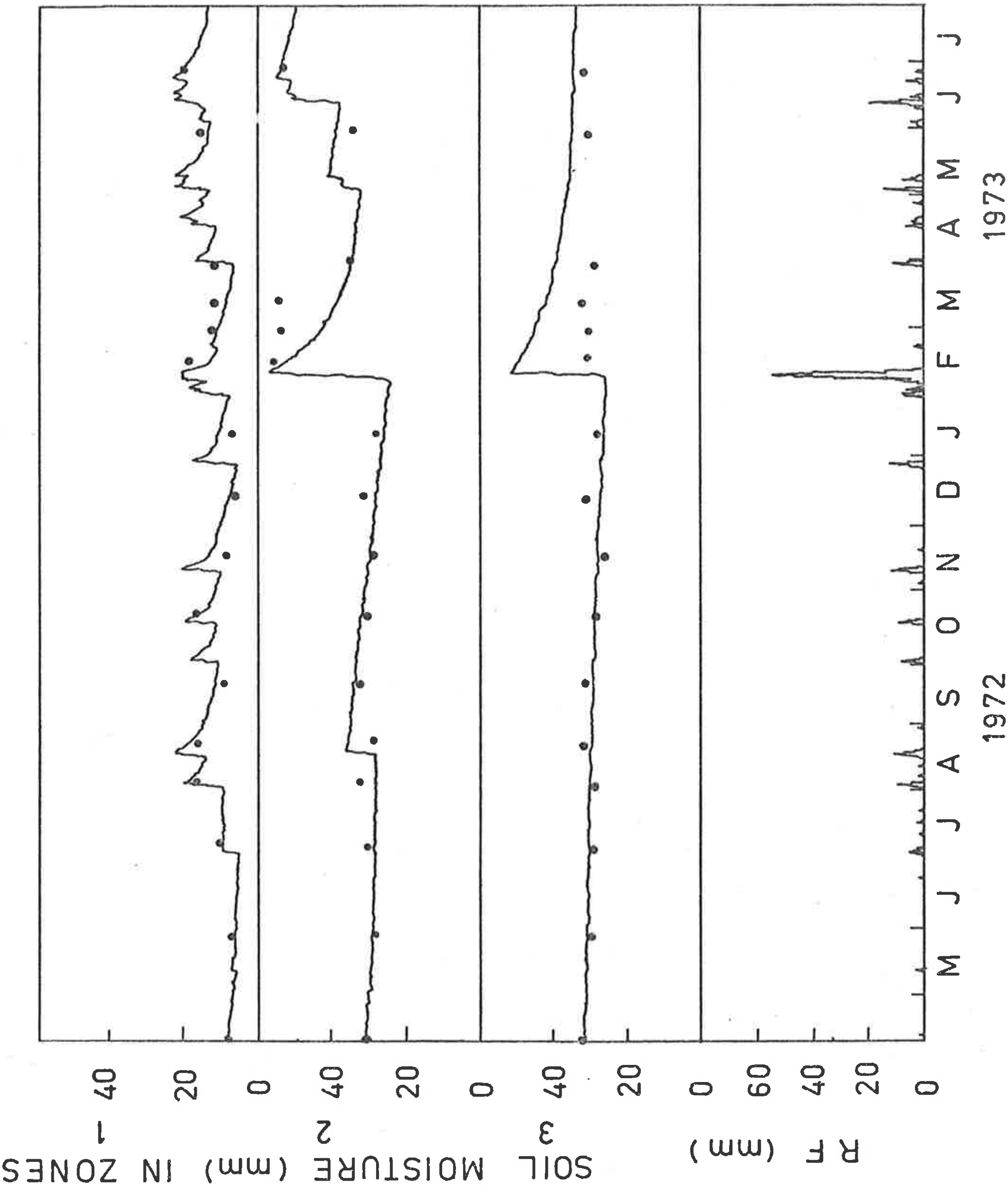

Fig. 5.14. The best fit obtained for the 'versatile budget' soil moisture model. The dots represent the measured soil moisture values in the 3 zones at the Wertigo paddock site, and the continuous trace is the model output.

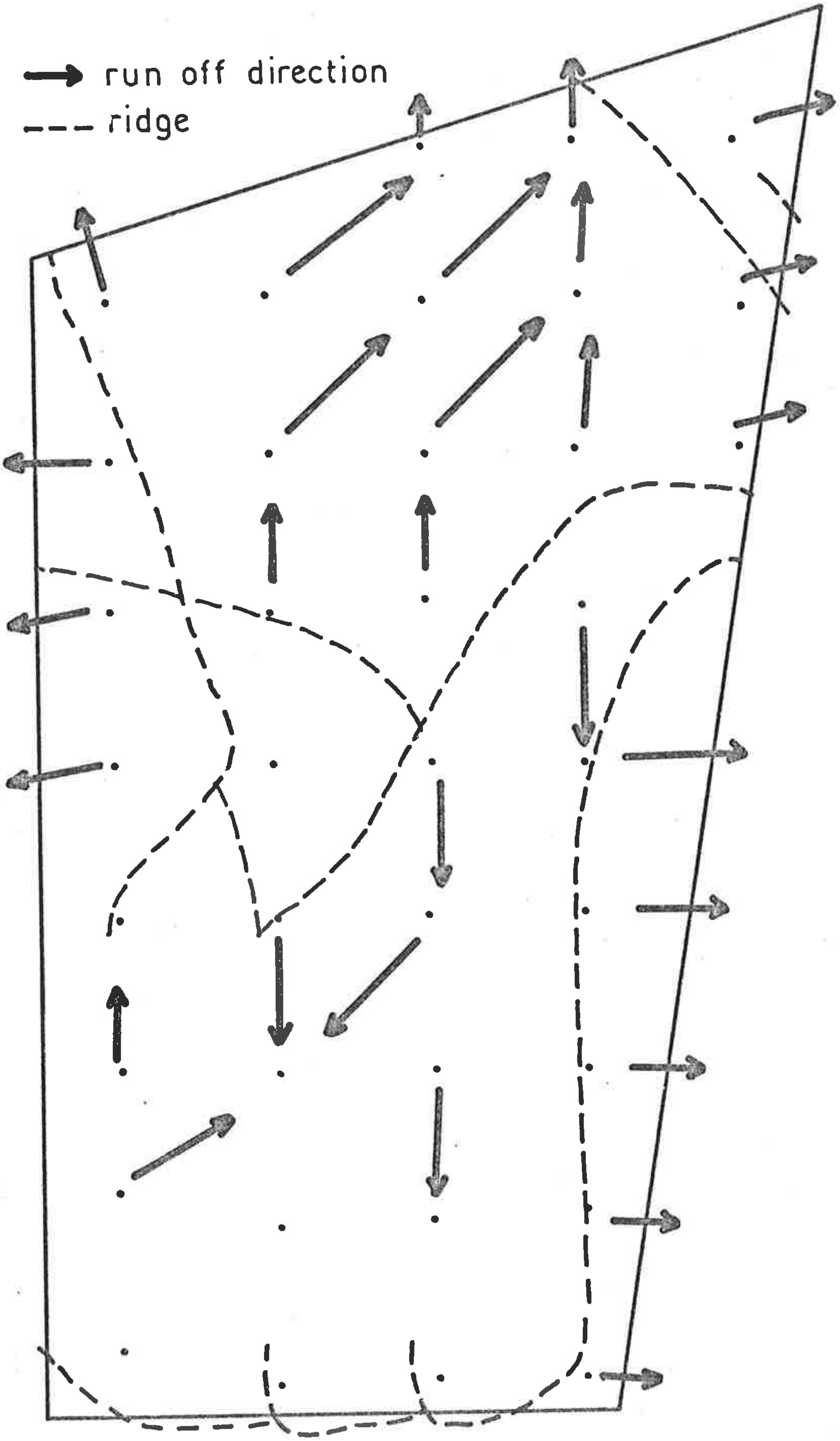

Fig. 5.15. The runoff directions used in the soil moisture model. Cells with no arrows leading from them drained internally. Run-on from areas outside of the paddock was not included in the model, but it would have only affected a few cells on the western boundary. (This figure can be compared with fig. 4.1).

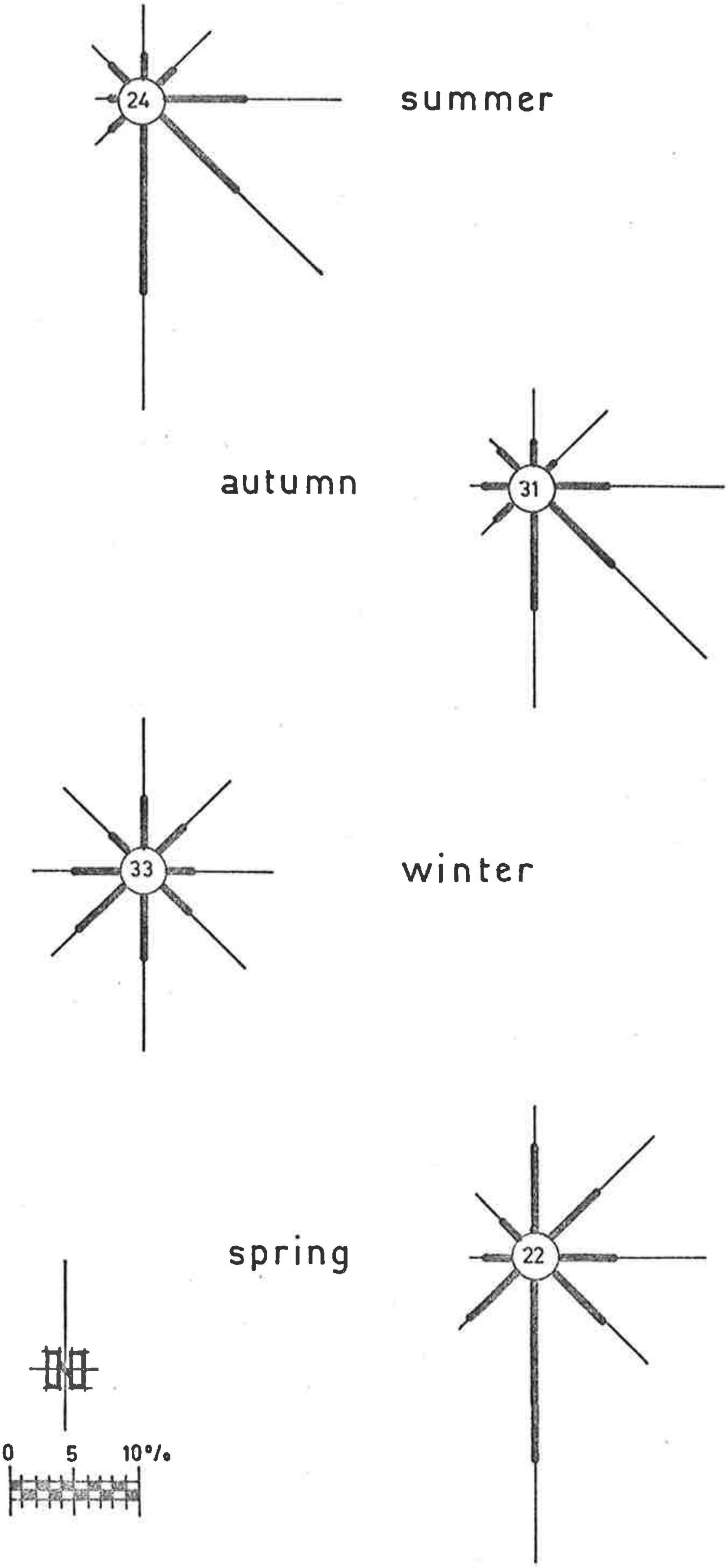

Fig. 5.16. The distribution of 9.00 am wind directions used in the model. The number in the centre of each rose is the percentage of calm days and the thin line represents wind speeds of greater than 9 knots (4.6 m s-1).

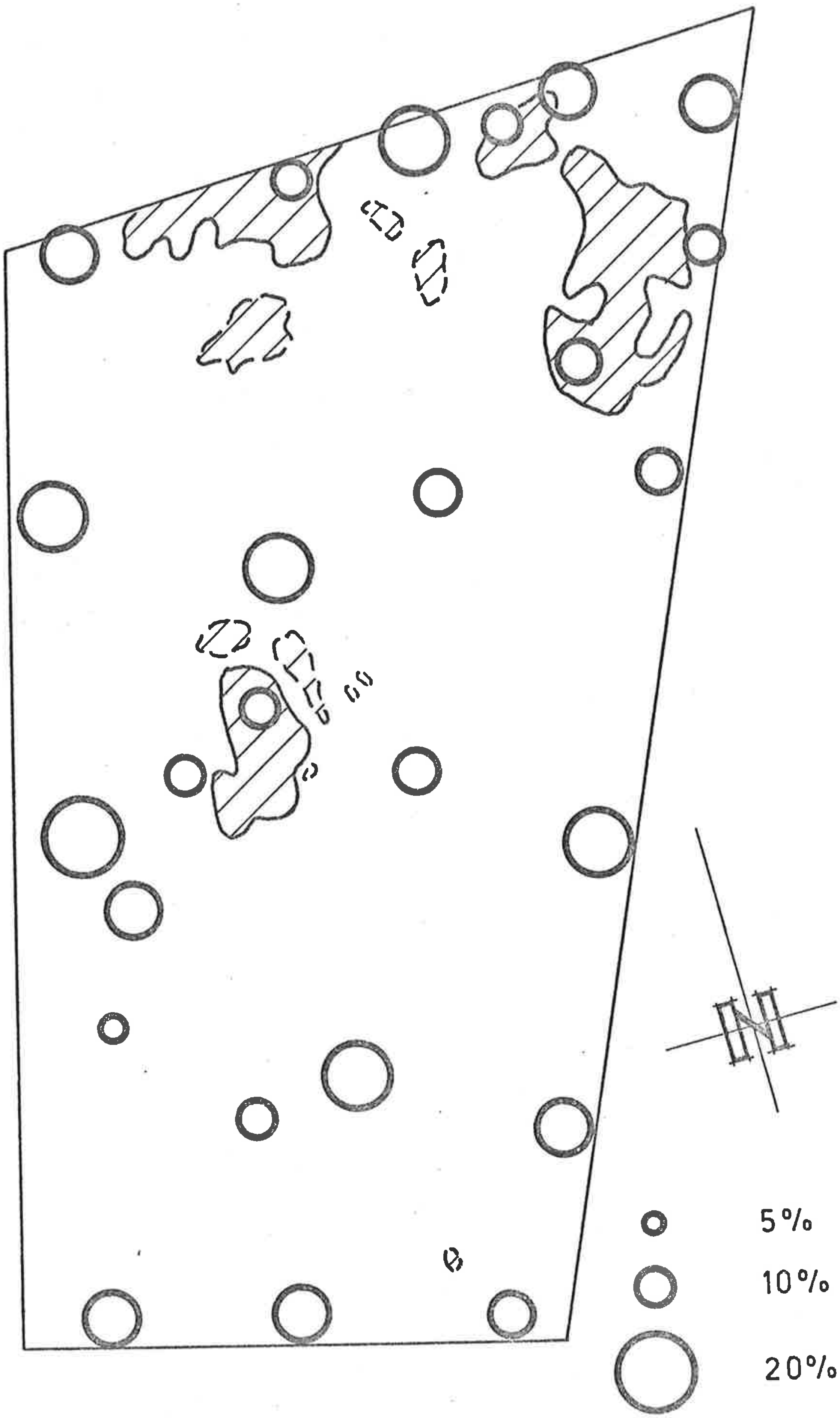

Fig. 5.17. The distribution of volumetric soil moistures measured in Wertigo in October 1973. The lowest values appeared to be associated with the wooded areas and the water course area south-east of the dam.

	previous day dry					previous day wet				
	a	b	c	d	e	a	b	c	d	e
January	0.950	0.011	0.011	0.017	0.011	0.875	0.013	0.025	0.050	0.037
February	0.954	0.009	0.013	0.010	0.014	0.819	0.014	0.056	0.054	0.056
March	0.958	0.015	0.009	0.010	0.008	0.813	0.054	0.040	0.053	0.040
April	0.943	0.021	0.014	0.014	0.008	0.767	0.029	0.078	0.087	0.039
May	0.913	0.029	0.030	0.020	0.008	0.787	0.073	0.047	0.060	0.033
June	0.899	0.047	0.026	0.022	0.006	0.753	0.094	0.053	0.065	0.035
July	0.878	0.053	0.037	0.027	0.005	0.810	0.084	0.052	0.058	0.005
August	0.902	0.037	0.026	0.030	0.005	0.796	0.060	0.072	0.048	0.024
September	0.906	0.031	0.025	0.029	0.009	0.851	0.021	0.043	0.057	0.028
October	0.926	0.020	0.023	0.024	0.007	0.877	0.009	0.044	0.035	0.035
November	0.941	0.013	0.018	0.016	0.012	0.851	0.032	0.064	0.032	0.021
December	0.948	0.014	0.015	0.013	0.010	0.855	0.000	0.015	0.060	0.060

Table 5.1. The probabilities of rainfall in the Markov rainfall model for Middleback. The classes are, a = no rain, b = 1 - 9 pt, c = 10 - 19 pt, d = 20 - 49 pt and e $\geqslant$ 50 pt.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Tot
starting minimum temperature	°C	8	8	8	7	5	1	1	2	5	8	8	8	
starting temperature range	°C	15	15	13	10	10	10	10	10	10	10	12	14	
maximum temperature allowed	°C	50	50	50	40	40	35	30	35	40	40	50	50	
simulated mean maximum temp.	°C	28.4	28.8	27.3	22.9	20.6	17.4	16.8	17.3	20.6	23.2	25.7	27.9	23.0
Whyalla mean maximum temp	°C	28.7	28.9	27.0	23.4	20.5	17.2	16.8	18.3	20.5	23.7	26.1	28.2	23.2
probability of a clear sky		0.50	0.50	0.40	0.40	0.40	0.35	0.35	0.35	0.45	0.45	0.45	0.50	
clear day critical temp.	°C	30	30	28	28	28	24	24	24	28	28	28	30	
simulated hours of sun		10.9	10.1	9.1	7.5	5.8	5.2	5.8	6.5	8.3	8.7	9.7	10.3	(2980)
Adelaide hours of sun		10.0	9.3	7.8	6.0	4.8	4.1	4.3	5.2	6.1	7.1	8.5	9.4	(2500)
													Whyalla	(3000)
simulated No. clear days		17	14	15	16	12	10	12	11	15	14	12	14	161
Pt Augusta No. clear days		17	14	15	15	10	9	11	10	12	11	11	13	148

Table 5.2. A summary of the parameters used in the temperature and cloud model, and a comparison of the simulated results and actual data.

Rainfall since the previous date

DATE	MIDDLEBACK	WERTIGO
6.4.72	---	---
8.6.72	18 pt	---
5.7.72	45	36 pt
3.8.72	79	84
21.8.72	95	86
19.9.72	5	12
17.10.72	79	79
14.11.72	61	64
12.12.72	4	4
10.1.73	63	36
14.2.73	583	>600
28.2.73	10	9
13.3.73	56	0
27.3.73	0	13
29.5.73	235	270
26.6.73	186	160

Table 5.3. A comparison of the rainfall recorded at Middleback homestead and at the Wertigo paddock site at which soil moisture was modelled.

GROWTH

6.0 *Introduction*

This chapter deals with all aspects of plant productivity including germination, establishment, growth, die back, leaf loss, and litter decay. A literature review indicated that very little information was available about these processes for Australian arid zone species. A lot of time was spent at the start of this project in attempting to find methods of gaining more detailed measurements of the growth of arid zone plants. This included methods of non destructively estimating biomass in the field and infra-red gas analyser techniques. However it became clear that large scale growth experiments should not be set up. There was a distinct chance that no suitable growth periods would occur within the time of the project, and it was clear that data for a much longer period than 2 - 3 years was needed. It eventuated that the South Australian arid zone had its wettest seasons on record resulting in the longest growth periods in memory. These were studied by other members of the department.

The GRZMOD1 model indicated that a high degree of accuracy was required in the estimation of the growth parameters, and that ephemeral growth and perennial growth posed different problems. Both these conclusions arise out of the essentially exponential growth models normally used in simulations.

This chapter inlcuded a review of the relevant literature supported by my own observations and personal communications especially from other people in the Botany Department. The problem of parameter sensitivity is discussed via a simple growth model, and the information available from a unique set of long term records is discussed. The growth submodel for four plant taxa is described and its validation is discussed.

Throughout this chapter the biomasses are given as oven dry weights of edible forage, unless indicated otherwise. For ephemerals the edible forage is taken as the above ground biomass, whereas for perennials it is the leaf and small twig biomass. This is established by stripping the bushes to approximately match the condition of bushes after heavy grazing. Growth rates are expressed in terms of changes in oven dry weight of edible forage. The edible biomass, as defined here, is also very similar to the biomass able to carry out photosynthesis.

6.10 *Review*

An enormous amount of work has been published on the quantitative aspects of the growth of plants, but most applies to laboratory experiments, crop plants or non arid pastures.

Blackman (1919) proposed the exponential growth function to describe the growth of single plants. However the growth rate is not constant, nor is the process purely exponential since new biomass is distributed between the leaves (productive) and other plant material (non-productive). West et al. (1920) proposed the term relative growth rate to overcome the implications of constancy. The exponential growth function may be summarized as,

$$dB / dt = r * B$$

$$B = B_o * \exp(r * t) \tag{E6.1}$$

where B is the biomass, and r the relative growth rate, and t is time. This equation usually only describes the early growth stages and not the seedling stages nor the more mature stages.

Many other indices and measures of growth rates, biomass and assimilation have been proposed. These have been summarized by Kvet et al. (1971) and Evans (1972). They are not relevant to the present problem since they deal with many variables, few of which have been estimated for arid zone species. Even if such data were available it is unlikely that it would be measured with sufficient precision to be included in the model. As discussed by Kvet et al. (1971), the variance, S_f^2, of a function, f $(x_1, x_2, \ldots \ldots, x_n)$, depends on the variances, S_x^2, of the primary values, and therefore errors in estimating the variables of the growth function would rapidly compound. Estimates of growth from empirical functions based on a few variables would better serve the purposes of the grazing model. Kvet et al. (1971) reviews papers describing growth as a function of time, i.e.

$$dB / dt = f\ (t) \tag{E6.2}$$

but these functions are only suitable for non limited or very constant environments.

An alternative approach, is to seek empirical equations correlating growth with exogenous parameters, especially meteorological parameters. Baier (1968) found that the yield of a wheat crop was best correlated with soil moisture, minimum and maximum temperature and only poorly with rainfall. In later experiments he found that the best triplet of meteorological variables for predicting wheat yields was AE/PE ratio, and the minimum and maximum temperatures.

Evapotranspiration rates are commonly used in growth models because of the recognized similarity of the water and CO_2 pathways in the plant, and the assumption that they will be controlled by similar factors (DeWit, 1958; Rose et al. 1972). However Byrne (1973) pointed out that a significant proportion of CO_2 is lost via the respiratory processes which are not so directly linked with the CO_2 uptake path. He suggested that growth was not only a function of evapotranspiration, but also of time.

Temperature is important since it is correlated with actual evapotranspiration through its effect on stomatal movements as well as via its effect on the rate of biochemical reactions. It is also correlated with solar radiation input although in arid regions radiant energy is usually not limiting. In the diffuse canopies of arid zone plants solar radiation and CO_2 would rarely be limiting. Most workers have assumed that arid zone plants are mainly soil moisture and possibly temperature limited, but Charely & Cowling (1968) and Cowling (1969) among others, have demonstrated that nutrient defficiencies can also be important.

6.11 *Review of plant growth models*

The modelling of plant growth has proceeded along several different lines. The most detailed is the approach exemplified by DeWit (1965), Duncan et al. (1967) and Waggoner & Reifsnyder (1968). These models described the penetration of solar radiation and the movement of CO_2 in the plant canopy, and the CO_2 and water pathways in the plant. The biochemical processes were dealt with more or less as a black box, as were the morphological changes in the plant. Paltridge (1970) has carried this type of study to the stage of modelling plant architecture, based on a set of simple assumptions about the development strategy. These approaches are far too detailed to be included in a grazing model.

Several plant growth models have been proposed as a part of a soil moisture study. The dependency of actual evapotranspiration on the amount of plant biomass utilizing the soil water store necessitates the inclusuion of a growth model in any detailed soil moisture model. Fitzpatrick et al. (1967) have described such a model for the Alice Springs area. This was discussed in section 5.471, where it was shown to be unsuitable for describing the Wertigo situation.

A number of plant growth models have been proposed to describe pasture growth. In these studies the emphasis has been on the pasture growth and not so much on the grazing animal. Begg & Jarvis (1968) described a model for Townsville lucerne (*Stylosanthes humilis*) based on measurements of leaf resistance to water vapour and CO_2 transfer in controlled conditions. The model was concerned mainly with the effects of different levels of radiation input. Rose et al. (1972) described a model for the same species where growth was related to the accumulated evapotranspiration. Byrne & Tongetti (1969) described another model of Townsville lucerne in a pasture at Katherine, N.T., Australia. They listed a series of assumptions about water uptake, transpiration rates and growth rates, which included the assumption that "other things being equal, the rate of increase in dry matter is closely proportional to the canopy available for photosynthesis", i.e., $dB/dt = F(p_1, p_2, \ldots \ldots, p_n) * B$. This is a very common assumption in growth models and relates back to Blackman's (1919) description of growth as an exponential process, the rate being modified by various limiting factors.

6.12 *Plant growth models in other grazing models*

The growth models used in simulations of grazing systems tend to be simpler than those described above.

All the grazing models discussed, with the exception of Van Dyne (1969b) use a growth function of the form,

$$\text{(E6.3)} \qquad \Delta B \text{ or } dB/dt = f(p_1, p_2, \ldots \ldots, p_n) * B.$$

The parameters, $p_1, p_2, \ldots \ldots p_n$ usually include the soil moisture at one or more depths, although Walters & Bunnell (1971) assumed that soil moisture is non limiting during the prescribed growth season. All the models examined included either temperature, solar radiation or evaporation rate, that is, a variable showing an annual, sinusoidal cycle. Some included a competition term which imposes an upper limit on the biomass produced (Walters & Bunnell, 1971; Vickery & Hedges, 1972). Only Van Dyne (1969a) and

Smith & Williams (1973) discussed nutrient availability as a parameter, and both assumed it to be constant or non limiting.

All of the grazing models considered the above ground (top) biomass and some of the more detailed models included the root biomass as well. Most models divided the tops into live (or green) and dead (or dry) pools, recognising that biomass does not become totally unavailable to the grazing animal as soon as it is no longer photosynthetically active. Goodall (1967, 1969) did not include any die back term at all. Only the model proposed by Van Dyne (1969a) simulated the germination and establishment of new plants. In all the other models, if the biomass of a particular taxon falls to zero, then it will not recover.

6.2 *Sensitivity*

Before discussing the growth model used in the simulation, the implications of the use of exponential models should be considered. The GRZMOD1 model showed that the net growth rates had to be accurately determined or else the biomass quickly fell to zero or rose to an upper limit. This is a normal feature in the growth of ephemeral plants, which start a period of growth with an above ground biomass of zero (or near zero), and grow rapidly, often to an upper limit imposed by competition effects. They then die back to zero above ground live biomass.

Perennial plants normally maintain a productive biomass of greater than zero, and a model estimating net growth as a function of existing biomass will have a tendency to show an exponential growth or decay. In the field, the biomass of the perennial plants would presumably tend to fluctuate around a relatively constant mean rather than an exponentially changing mean. Any changes in the long term mean biomass are on a successional time scale.

A model which has been validated against long sequences of real biomass data, should not have any pronounced trend in the mean biomass during the period over which it was validated. However a slow trend is difficult to detect in biomass data showing enormous variability from season to season. Slow trends are an important factor if the model is to be used to compare the effect of different management treatments. The sensitivity of the mean biomass to changes in the net growth rate was investigated by the following simple model.

The first step was to estimate the mean net growth rate, where the net growth rate was defined as the net biomass change per unit time by plants recently protected from grazing. It is assumed here, and throughout the growth model, that the productive biomass of perennials and ephemerals is the same as the edible biomass. In species such as *Atriplex vesicaria* or *Kochia sedifolia* this means that most of the "woody" biomass and all of the below ground biomass is not considered. Carbon fixation that results in an addition to these biomasses is regarded as a cost of survival similar to respiration losses. In this simple model it was argued that since the biomass in paddocks like Wertigo had remained relatively constant for more than 50 years, then the grazing pressure must just balance the mean net growth rate.

It was assumed that sheep graze green ephemerals when they are present, and the K.V.R. records indicate that, over a period of 25 years, green ephemerals were available for about $^1/3$ of the time. The average daily intake of a sheep is 1.2 kg sheep^{-1} day^{-1} (Section 7.42), giving an annual consumption of about 300 kg sheep^{-1} year^{-1} of perennials. The stocking rate in Wertigo is 6 to 10 ha sheep^{-1}, although this is not uniformly distributed over the paddock. Therefore the annual consumption per hectare is 30 to 50 kg ha^{-1} year^{-1}. The edible perennial biomass in Wertigo is 500 to 1000 kg ha^{-1} dry weight, which means the consumption represents about 3% to 10% of the edible biomass. Therefore the average biomass increment of a bush protected from grazing should also be about 3% to 10% per year - say 7%.

The effect on the biomass of errors in the estimated mean annual growth rate after a simulation run of n years may be estimated as follows. A difference equation model equivalent to the exponential growth model is assumed;

$$B_1 = B_0 * (1 + r) - C$$

$$B_2 = B_1 * (1 + r) - C$$

therefore, $B_n = B_0 * (1 + r)^n - C * [(1 + r)^{n-1} + (1 + r)^{n-2} + \ldots \ldots +1]$ where B is the above ground biomass, C the consumption and r is the mean growth rate. This equation simplifies to;

$$B_n = B_0 * (1 + r)^n - C * [(1 + r)^n -1) / r]$$

and using the approximation, $(1 + r)^n \approx (1 + n * r)$,

$$B_n \approx B_0 * (1 + n * r) - n * C$$

If a systematic error, d, occurs in estimating r, then the percentage error is,

$$= 100 * (B_n' - B_n) / B_n$$

where, $B_n' = B_0 * (1 + n*r + n*d) - n*C$. Therefore the percentage error is,

$$= 100 * [B_0 * (1 + n*r + n*d) - B_0 * (1 + n*r)]$$
$$/ [B_0 * (1 + n*r)]$$

$$= 100 * (n * d) / (1 + n * r) \qquad \text{(E6.4)}$$

(It must be emphasised that this is only an approximate estimate of the sensitivity. Equation 6.4 was also derived, taking the variability of r into account, i.e.,

$$B_1 = B_0 * (1 + r_1) - C$$

$$B_2 = B_1 * (1 + r_2) - C$$

and $$B_n = B_0 * \prod_{i=1}^{n} (1 + r_i) - f(C).$$

If second and higher order terms of the expansion of $\Pi(1 + r_i)$ are ignored, then,

$$B_0 * \Pi(1 + r_i) \approx B_0 * (1 + n * r)$$

where, $$r = \Sigma\, r_i \,/\, n.$$

The value of f(C) is dependent on the sequence of r_i values, and especially on the r_i values for i near n (i.e. on the growth rates in the most recent years). Simple simulation models of this system confirmed the results presented here.)

Runs of about 10 years are needed to test the effectiveness of different management policies in a climate as variable as the arid zone (e.g. Swartzman & Van Dyne, 1972). If the percentage error at the end of the 10 year run is to be less than ± 10%, and the mean annual growth rate is taken to be 7%, then the growth rate must be measured with an absolute error of less than 1.7%. This is not possible with any techniques that might be applied to arid vegetation over this time scale (see Section 7.31). Models with a shorter time increment demand even smaller absolute errors in estimated growth rate.

This result implies that perennial growth models of this type must be recognised as being potentially misleading when run for long periods of time. Such models should be tested for an exponential increase or decrease by running them for a period much longer than that over which they are to be used, in order to assess the rate of change of the mean biomass independent of any treatments.

6.30 *Sources of plant growth data*

The review sections of this chapter, and especially the previous section, have indicated that the approach to the growth model most likely to be successful would require long term records of plant growth. A model based on the information available about the detailed growth process could be compared with these records and the model parameters adjusted to give a better fit.

Long term studies of plant growth are very rare in all ecosystems throughout the world. The Jornada Range in the semi-desert grasslands of Arizona is one of the longest running and best reported sites in arid or semi-arid areas. Even at this site, detailed vegetation records have been kept only since 1941, and growth records since 1958.

In Australia the major long term studies in arid or semi-arid areas are the Yudnapinna experiment (see Section 4.5) and the Koonamore experiment. At Yudnapinna biomasses were recorded annually for 12 years, but most of the results are no longer available. Therefore the Koonamore data were more useful.

6.31 *The Koonamore data*

The T.G.B. Osborn Vegetation Reserve at Koonamore (K.V.R.) was established in July 1925 when the main herbivores, sheep and rabbits, were fenced out of a badly eaten out section of 510 ha in the corner of a paddock in the north east of S.A. (35° 15' S, 139° 27' E). From 1926 photographs were taken at photo-points and of quadrats at frequent intervals. Some quadrats were also charted. Photographs were taken at approximately three monthly intervals until 1931 and annually thereafter. Since the early 1950's the records are less regular. All of the records are stored in the Botany Department, University of Adelaide.

The results of the study of regeneration are described by Osborn _et al_. (1935) and Hall _et al_. (1964). Relatively little attention has been paid to the ephemerals with most emphasis being on the tree and large shrub species. It is clear that there remains a large block of neglected information, especially in the photographs. Some of this information is analysed and presented in this thesis.

6.32 *Ephemerals*

An inspection of the photo series indicated that the inputs of ephemerals could be followed. The dominant ephemeral is *Stipa nitida*. (Again the word ephemeral is used in the sense described in sections 4.1 and 6.2. This species is an erect grass up to 1 m high and it occurs as scattered individuals forming dense tussocks. *S. nitida* is readily recognised in black and white photographs. The panicle is loose, 10-30 cm long and silky in appearance making the flowering stage easy to recognise.

S. nitida was chosen as the first species for study, although other ephemerals were later included. In the only autecological study of *S. nitida*, Osborn _et al_. (1931) described it as the most important fodder grass in the north east of S.A. It also occurs in Wertigo paddock, but does not appear to reach such high biomasses. Osborn _et al_. observed that

> "... germination in the field is best following late summer rains. The active growing season extends throughout the autumn and winter months. Flowering occurs towards the end of the cold season and spring months, and the first fruit are shed in the early summer months."

This was checked in the photographs for the period 1926 to 1931, when photographs were taken every 3 months. It was found that *S. nitida* could also germinate in late winter and early spring, and then grow rapidly and shed fruit in summer. A sequence of 9 different phases of its phenology were recognised and could be approximately aged.

Twelve different photo-points or quadrats showing *S. nitida* growth on loamy soils were then examined independently. The phase was estimated in up to 49 photo-dates covering the period 1926 to 1951. The photo-dates were less frequent after 1951 and these records were kept aside for subsequent validation of models based on the 1926 - 1951 photographs. It was found that there was excellent correlation of the phase between the photographs for the same date but different sites.

The approximate germination dates were estimated and these were checked against a soil moisture budget for K.V.R. loamy soils. The soil moisture budget was based on that derived for Wertigo. No soil moisture data were available to check the soil moisture model for K.V.R. soils. The histories of different growth inputs for *S. nitida* were then drawn up (fig. 6.1).

It was clear from the photo-points that the biomass of *S. nitida* and its percentage contribution to the total biomass varied from growth event to growth event. The other main species are bassias (mainly *B. patenticuspis* and *B. schlerolaenioides* and to a lesser extent *Erodium cygnorum*, *Zygophyllum* spp, and *Salsola kali*. The photo points were reviewed and the dominant ephemeral was noted. These are also shown in figure 6.1, where S refers to *S. nitida*, or in a few cases other grasses, while all the other ephemerals were grouped under B since bassias were by far the second most common ephemeral.

It appears that *S. nitida* does best during growth events initiated by, or at least including summer rains, while the bassias do better in winter rains. This is in general agreement with the observation of Osborn et al. (1931, 1935). They describe *S. nitida* as a predominently summer growing species while most bassias, except *B. patenticuspis*, germinate and grow best in the cooler months. Even *B. patenticuspis* was observed to do well in winter rains.

The germination results only partially support the conclusions of Osborn et al. (1931). It appears that

S. nitida is able to germinate in autumn as well as in the late summer - spring period. The table below shows the distribution of the estimated germination dates throughout the year.

J	F	M	A	M	J	J	A	S	O	N	D
-	4	2	1	1	-	-	3	-	1	-	-

12 significant *S. nitida* growths occurred during the 26 years of records examined, although more germination may have occurred since some were missed when they were hidden by the growth resulting from an earlier germination. This is especially the case with the autumn germinations, which were observed only in years in which no good rains occurred in summer or spring. Some of the germinations attributed to August may have occurred in June or July but slow growth during the winter months made this hard to estimate.

Up to this point the study had made use only of the growth phase of the ephemerals and no attempt had been made to distinguish between the biomass of ephemerals produced in the various growth events.

Photographs have been used to estimate biomass with some success. Fatchen (unpublished Honours thesis, University of Adelaide, 1971) used colour 'polaroid' photographs of plots which were later clipped and weighed as an aid in estimating the biomass of a large number of samples which could not be clipped. It was not possible to match any of the K.V.R. photos to existing ephemeral stands so the biomass could not be quantified.

An alternative approach was to rank the photographs for any particular photo-point comparing them with similar rankings at other photo-points so that an overall ranking of ephemeral biomass could be drawn up. This proved to be possible, but it was realised that the approach could be improved by the following method.

Photo-points having an almost complete sequence of annual photographs for the period 1926 to 1951 were chosen. If more than one photograph was taken in any year, the photograph nearest August 31st was used. Consecutive pairs of photographs (e.g. 1926 - 1927, 1927 - 1928, 1928 - 1929 ...) were examined and it was estimated whether the biomass had increased (/), remained the same (—), or decreased (\) over the period. Originally 5 categories were used but it was found that 3 categories were more reliable. The method appeared to give repeatable results in that the same results were obtained if the photo-sequence was re-examined several weeks after the first attempt at ranking, and in that photo-points in the same locality (e.g. the north-west and north-east corners of a 10 m X 10 m quadrat) gave very similar results.

The first ranking gave a series of data similar to that shown in line 1 of figure 6.2. The same photo-series was then re-examined comparing pairs of photographs two years apart (e.g. 1926 - 1928, 1928 - 1930 etc.) and then phase shifted by one year (i.e. 1927 - 1929, 1929 - 1931 etc.). This was repeated, with appropriate phase shifts for 3 and usually 4 year separations, giving lines 2 to 10 in figure 6.2. Selected periods of more than 4 years were also used.

A locus of biomass against time was established by the following process. The sequence / \ \ in line 1 implies a run of years of the form  , but the first comparison in line 2 implies that the rise in year 1 was greater than the fall in year 2, i.e.  . Line 4 implies that the combined falls in years 2 and 3 did not equal the rise in year 1, i.e.  . The next year showed a fall and line 7 shows that the biomass finally falls below the original biomass, thus the locus for the first five years is  , which is confirmed by lines 2 and 3. In the same way longer and more complicated loci may be derived.

The procedure was tested by making arbitrary traces on graph paper and producing data sets equivalent to those above, and from them deriving the loci. The technique adequately described the major peaks and troughs of the original traces, although there was obviously no indication of scale, nor of the relative size of the highest peak or of the lowest trough. In arid zone ephemeral vegetation the lower limit is usually zero or near zero, while the upper limit is known approximately from readings taken in the recent run of good years.

This procedure was carried out for the ephemerals at 4 photo-points. No attempt was made to distinguish between *S. nitida* and other ephemerals since the apparent biomass of *S. nitida* tended to be much higher than that of the other ephemerals, and the species composition of the other ephemerals varied from year to year. However the years in which the other ephemerals made a significant contribution were noted. All the loci from the different photo-points are essentially similar (fig. 6.3 & 6.4).

6.33 *Perennials*

The main perennial shrubs at both K.V.R. and Middleback are *Atriplex vesicaria* (saltbush) and *Kochia sedifolia* (bluebush), with lesser amounts of *Atriplex stipitata*, *Kochia pyramidata* and, at Middleback, *Chenopodium ulicinum*.

Only *A. vesicaria* has been the subject of detailed autecological and physiological studies. It is a palatable forage with a high salt and protein content. It is drought resistant and is the major forage shrub in much of southern Australia.

Osborn et al. (1932) made an autecological study of *A. vesicaria*. They found it was shallow rooted and able to draw upon water only in the top 10 to 20 cm of soil, although Cowling (1969) and Jones & Hodgkinson (1969) have reported roots penetrating to about 1 m. Carrodus & Specht (1965) compared the root systems and water uptake methods in *A. vesicaria* and the deeper rooted *K. sedifolia* and found that the rooting depth was an important factor in controlling the relative distributions of the two species. *K. sedifolia* was more drought resistant due to a deeper root system, but it was not able to establish itself as rapidly as *A. vesicaria*. *K. sedifolia* was dominant on deeper soils where it could out survive *A. vesicaria*, while on shallower, more frequently droughted soils, *K. sedifolia* could not become dominant.

The germination of many *Atriplex* species, including *A. vesicaria*, was studied by Beadle (1952). He found that the germination was little affected by temperature, but required long periods of near saturated soil moisture conditions. He concluded that *A. vesicaria* would not germinate in summer because the moisture conditions would rarely occur. Hall et al. (1964) noted that *A. vesicaria* germinated rapidly after winter rains, but often died if drought periods followed. *K. sedifolia* also requires heavy rains for germination, but unlike *A. vesicaria*, its seeds are only viable for a few months. Thus, regeneration of *K. sedifolia* is rare, and none had been observed on K.V.R. up to 1964.

Both *A. vesicaria* and *K. sedifolia* are very long lived plants, although seed mortality is high. Hall et al. (1964) reported that some *A. vesicaria* plants had survived in K.V.R. for 16 to 24 years. A preliminary review of the K.V.R. quadrat charts carried out at the start of the project, indicated that the mean life span of *A. vesicaria* bushes which had survived for at least one year, was more than 22 years. It was apparent from the K.V.R. photographs that *K. sedifolia* was longer lived.

The quadrat 10A photographs at K.V.R. provided a regular sequence from which the *A. vesicaria* biomasses were estimated by the method described in section 6.32. The 10A photographs were supplemented by some other photo-points after 1953 when a fallen tree was placed in quadrat 10A as an 'experiment'. The results are summarized in figure 6.5.

6.40 *The growth model*

This section summarizes the assumption and information used in building the growth model. The model is not meant to be a complete representation of the growth system as it is at present understood; nor is it a "best fit" model. It is a compromise between an authentic representation of the real world, fit to available data, and the restrictions due to inadequate data. It shows some of the major processes in the arid zone growth system, while omitting others.

The ephemeral and perennial sub-models are summarized in figure 6.6. Those interactions included in the sub-models are discussed below, however, certain interactions have been omitted. One such interaction is the effect of the total biomass on the evapotranspiration rate and, therefore, on the soil moisture levels. This has been omitted because no data showing this interaction in arid shrub communities was available. For example, the relative amounts of water lost through the plants and through the soil surface under different conditions is not known. The soil moisture model (section 5.47) gives a reasonable fit to 16 months of Wertigo data even though this interaction has been omitted. The most significant effect its inclusion would have had on the growth model would be in the competition between the different species for limited water supplies. This would lead to the dominance of different species due to this competition, and to a limit on the absolute amount of plant biomass produced before the water supplies were exhausted. Nevertheless these processes are included in the model described below. The competition for dominance is accounted for in the relative growth rates of the different species and the change of this rate with soil moisture, temperature and nutrient availability. The absolute limits on total biomass are accounted for in a special 'competition' function. Therefore, even though this process has been omitted from the model, its effects have been included elsewhere and the parameters fitted appropriately.

A second, important process omitted from the growth model is the effect of sheep grazing on the subsequent regrowth of the different species. Osborn et al. (1932) demonstrated that a certain amount of grazing was apparently advantageous to *Atriplex vesicaria*, while Trumble & Woodroffe (1954) showed that grazing appeared to increase the density of *Kochia sedifolia*. However, neither of these experiments is conclusive (Noble, 1974). Leigh & Mulham (1971) showed that severely defoliated *A. vesicaria* suffered a high mortality. There is little other relevant data for Australian arid zone species, and given the complexity of the sheep-plant interactions, there was no basis on which any model could be proposed. The omission of this interaction must be borne in mind in interpreting any of the grazing model results.

It is unfortunate that these two interactions, critical to practical grazing management, have been omitted. Some managers argue that the bush should be removed, thereby reducing the competition for limited recources and encouraging more grass. Another commonly held belief, is that "the country" does best under light grazing. These interactions are only partially modelled and this imposes severe limitations on the use of the model as an aid to management decision making.

6.41 *Ephemeral germination*

In this section the word 'germination' will be used to mean both the germination and establishment (or survival) of the plant; that is the growth phase up to the point where the seedling no longer has access to the nutrients stored in the seed. Koller (1955) reviewed the regulation of seed germination, describing moisture, temperature, mechanical factors, light, exogenous chemicals and gases, and dormancy, as some of the important factors. Once the seedling has emerged through the soil surface a different set of microclimate parameters becomes important.

Many studies of arid zone seed germination have been done in the laboratory, where the seeds have been subjected to a range of temperature, soil moisture and light regimes (Hammouda & Bakr, 1969; Tapia & Schmutz, 1971; Mott, 1972). These results are difficult to relate directly to the field situation. Sometimes germination and survival have been studied as part of another investigation, e.g. Mott & McComb (1974) investigated the germination and survival of several ephemeral species in a study of patterns in arid zone vegetation.

Stipa nitida was described by Osborn et al. (1931), as best germinating after summer rains. A study of the K.V.R. records from 1926 to 1951 confirmed this, but showed that *S. nitida* could also germinate after winter rains, although usually more slowly. Osborn et al. also showed that germination required "saturated soil" for at least 2 to 3 days and that the optimum temperature range was limited and centred at 24°C. *S. nitida* appears to differ markedly from *S. neaei* studied by Soriano (1962). This species needed only a small imbibation to germinate in a few hours, and would do so over a wide temperature range.

A simple model of the form; "germination will occur if the soil moisture in zone 1, SM_1, is greater than a critical value for at least x days", was found to be inadequate to describe the observed sequence of *S. nitida* inputs at K.V.R. A temperature factor was included so that the model was of the form; "germination (i.e. emergence through the soil) will occur if the SM_1 is greater than a critical value (taken as the wilting point for zone 1, WP_1) for a period such that the sum of 'mean daily temperature minus a critical temperature' is greater than a critical value". If the critical temperature is high and the critical sum is low, then mainly summer germinations will occur, while if the critical temperature is low and the critical sum is high, mainly winter germinations will occur.

By a process of trial and error a model of this form was derived for *S. nitida* and bassia germination. A critical temperature of 20°C and a critical sum of 200 gave the best fit for *S. nitida*, while 0°C and 1350 gave the best result for bassia. The fit to the K.V.R. data was not perfect (fig. 6.1), however the real test is the fit of the growth model as a whole. The results are similar to those of Mott (1972) who found that in an arid region of Western Australia the temperature of the moist seedbed was the major factor in determining the composition of the flora, and that summer rains produced a predominance of grasses, while winter rains produced more dicotyledons.

In the model it is assumed that both germinations produced 5.0 kg ha^{-1} of biomass and that the plants remain in seedling stage for 7 days. During this time the biomass increases by 40% per day if $SM_1 \geqslant WP_1$, or decreases by 20%

if $SM_1 < WP_1$. These rates are independent of temperature and nutrient availability. At the end of the 7 days, from 1.0 to 53 kg ha^{-1} of biomass is transferred to the mature stage.

6.42 *Ephemeral growth rates*

There were no published estimates of the growth rates of mature arid zone plants suitable for inclusion in the model, so the rate had to be estimated indirectly. From field recordings and the K.V.R. photographs it appeared that *S. nitida* could increase from about 50 kg ha^{-1} to 1000 kg ha^{-1} in 2 months. This implies an average daily growth rate of about 5% per day if a model of the form,

$$B_{t+1} = k * B_t \qquad \text{(E6.5)}$$

is assumed. A 'guesstimate' of this sort was used as a starting point in fitting the model to the observed K.V.R. data. The maximum growth rates eventually used were 8% for *S. nitida* and 5% for bassia. The maximum growth rate is reduced by multiplicative soil moisture, temperature, and nutrient factors, all varying between 0.0 and 1.0. All the rate equations described below are expressions for k, or one of the multiplicative factors.

Many authors have shown that the evapotranspiration decreases as the available soil moisture falls from the field capacity to the wilting point, and have presumed that the growth rate also falls, although this has been disputed by others (see the review by Baier, 1968). The majority of the ephemeral roots are in the top 10 cm of soil so only the soil moisture in zone 1 is assumed to be potentially available to the ephemerals. In this model for both *S. nitida* and bassia, the rate is assumed to be constant over the whole range of available soil moisture, and growth stops if soil moisture falls below wilting point. This gives a better fit than when a linear reduction of growth rate with soil moisture depletion is used. Since the simple assumption gave an adequate fit, no more complex functions were used.

The variation in growth rate about the optimum temperature is assumed to be hyperbolic,

(E6.6) temperature factor = AMAX1 (1.0 - TW * [TM - TE] **2, 0.0)

where, TM, the optimum temperature for growth was 23°C for *S. nitida* and 22°C for bassia, TW is 0.01 in both cases, and TE is the mean daytime temperature (fig. 6.7).

The nutrient factor is described in section 6.44, and the competition factor in section 6.45.

Dieback occurs when $SM_1 < WP_1$. The K.V.R. photographs indicated that dieback is faster in summer than in cooler periods. A linear relationship between dieback rate (i.e. negative growth rate) and mean daytime temperature, TE, is assumed, and the fitted equation is,

(E6.7) dieback = 1.0 - 0.0008 * TE

for both species. There was also a constant loss rate of 0.5 kg ha^{-1} day^{-1} for *S. nitida* and 0.3 kg ha^{-1} day^{-1} for bassias. This loss was effective at low biomasses, and caused the biomasses to fall to zero, rather than to asymptote, exponentially towards zero. The ephemeral biomass lost in dieback is transferred to the standing dead pool.

The decay rate of the standing dead material in the photo series appeared to be increased by rains, so a linear relationship of the form,

$$\text{proportion surviving (not decaying)} = 1.0 - (0.005 + 0.002 * \text{RF})$$

where RF the daily rainfall in mm, is used.

6.43 *Perennial growth*

This section deals mainly with *Atriplex vesicaria*, because this was the only perennial species for which validation data were available. The *A. vesicaria* model was fitted to the K.V.R. data and the *Kochia sedifolia* model was added later. The whole model was then checked for stability by running it for periods of 10 to 100 years with data generated by the RFALL and TEMPER models described in sections 5.2 and 5.3.

The germination and establishment of *A. vesicaria* was not modelled. A preliminary review of the K.V.R records indicated that individual *A. vesicaria* plants had a mean life of about 20 to 25 years once they had survived the high mortality of the first few years. Crisp (pers. comm.) later studied both *A. vesicaria* and *K. sedifolia* germination and survival in more detail. His results confirmed my preliminary survey, and showed that *K. sedifolia* had a very much longer mean life span.

Several physiological and growth studies of Australian Atriplex species exist, the interest being due in part to the C_4 pathway of carbon fixation shown by some members of the genus. Jones et al. (1969) described a series of experiments comparing the growth rates of some Atriplex species and other C_4 and C_3 plants. Unfortunately *A. vesicaria* was not always among the species studied, but when it was not included, *A. nummularia* has been taken as a useful guide.

The average growth rate recorded for *A. nummularia* under "plantation conditions", as estimated from fig. 4 of Jones et al., was 0.0083 g g (d. wt.)$^{-1}$ day^{-1} over a period of 380 days. This is taken as an estimate of the maximum growth rate for *A. vesicaria*. Hofstra & Hesketh (1969) measured the net photosynthetic rate of individual *A. nummularia* leaves over a range of temperatures from 20°C to 50°C. This data has been taken as the basis for a temperature factor. The factor is multiplicative and lies between 0.0 and 1.0, as in the ephemeral growth model. The factor is,

$$\text{(E6.8)} \qquad \text{factor} = \text{AMAX1}([0.166 + 0.0206 * \text{TE} + 8.245 / [\text{TE} - 59.0]] / 0.6,\ 1.0)$$

where, TE is the mean day time temperature (fig. 6.7).

A. vesicaria has a rooting system extending down to at least the second zone modelled by the soil moisture model. Cowling (1969) demonstrated that *A. vesicaria* maintained a deep rooting system and an ephemeral shallow rooting system. The plant was able to draw water from the deeper zones while it was available. If the upper surface was wetter, then in three to four days the bush could grow a new set of surface roots to utilize this moisture. These surface roots were responsible not only for the uptake of water, but also of nutrients. The K.V.R. photo-record showed that the growth of *A. vesicaria* was closely linked with the soil moisture store in the second zone, as calculated by the soil moisture model.

It is assumed in the model, that *A. vesicaria* can maintain itself with no loss of biomass whenever either zone 1 or zone 2 hold available water. Growth can only take place if nutrient uptake can occur, i.e. if the upper store has been moist for at least 4 days, and nutrients are available. The growth rate is dependent on the soil moisture stored in the second zone, as shown in figure 6.8. It was found that an adequate fit could be obtained if growth was assumed to continue unimpeded over almost the whole range of available soil moisture.

A. vesicaria is drought resistant, but in very dry conditions it will shed leaves, so reducing its water requirements even further, If both zone 1 and zone 2 were dry the model assumes that *A. vesicaria* dieback occurred. The rate of dieback is taken to be constant, (E6.9) $\text{dieback} \equiv \text{growth rate} = 1.0 - (0.00014).$

The material lost in dieback is transferred directly to the litter pool.

6.440 *Plant nutrition*

Initially the model was run without the inclusion of a nutrient factor, and attempts were made to fit it to the 1926 to 1951 K.V.R. data. This proved to be difficult since the biomass was very unstable, tending to either rise to an upper limit or to fall to near zero. When a balance was achieved, the modelled response agreed with the K.V.R. data in that it responded to observed wet and dry periods, but the relative magnitudes of the biomasses in these responses compared with the observed data very poorly. It was suspected that this may have been due to the omission of the nutrient factor, so a nutrient submodel was included.

Some workers (e.g. Hilgard, 1941), have argued that arid zone soils have low leaching potential and should, therefore, retain sufficient minerals to prevent any nutritional limitations to growth. Large biomasses produced after good rains are taken as evidence for this view. This view has been challenged. Trumble & Woodroffe, (1954) observed that the growth response decreased in the second of two consecutive wet years. They argued that the nutrients were largely locked up in living and dead biotic material which was turning over at a very slow rate. Beadle (1948), Beadle & Tchan (1955), and Charley & McGarity (1964) have all commented that the Australian arid zone soils seem to be nutrient deficient. Beadle (1966) discussed the part of low phosphorus levels in forming the Australian flora. However, nitrogen appears to be the more important nutrient limit. The role of nitrogen in Australian arid zone communities has been reviewed by Charley (1972) and Charley & Cowling (1968).

Nitrogen is taken up by plants as NO_3^- and sometimes as NH_3. This available nitrogen is produced by bacterial action (mineralization) on organic material at a rate dependent on soil moisture, the history of wetting and drying, soil temperature, total nitrogen content and the availability of other nutrients such as phosphorus (Cowling, 1969) or Molybdenum (Nicholas, 1957). The rate of mineralization has been measured in incubation experiments under various conditions, and, when converted to $kg(NO_3^-)\ ha^{-1}\ day^{-1}$ in the top 10 cm of soil, the rate varies from 5 to 20 $kg\ ha^{-1}\ day^{-1}$ (Cowling 1969), to 0.5 to 4 $kg\ ha^{-1}\ day^{-1}$ (Charley, 1972). Clearly these determinations have little relevance to the rate actually occurring in arid zone soils. There is also an input due to nitrogen fixation by microorganisms in the top layer of soil. Tchan & Beadle (1955) estimated the rate of nitrogen fixation by free living organisms (mainly blue green algae) to be a maximum of 3.0 $kg\ ha^{-1}\ yr^{-1}$. The role of legumes and other symbiotic nitrogen fixing systems is unclear. Beadle (1964) estimated the effectiveness of many nodulated legumes in nitrogen fixation, while Rogers et al. (1966) have shown that some lichens are nitrogen fixers.

The approximate mineralization rate can be estimated from the nitrogen turnover in an arid zone community, since in the long term these two rates must be approximately equal. The annual nitrogen turnover was estimated by Charley & Cowling (1968) to be 36% of the above ground nitrogen in an *Atriplex vesicaria* community. This is in agreement with the estimate of 30% by Rodin & Basilevich (1965) for semi-shrub deserts. Correll (1967) estimated the above ground nitrogen in different communities on Yudnapinna Station (100 km north of Middleback). The results varied from 255 kg ha^{-1} for a black-oak woodland community, to 16 kg ha^{-1} for an *Atriplex vesicaria* community. Table 6.1 shows the calculation of the above ground nitrogen in Wertigo, based on the data of Correll and measurements at Middleback.

This calculation does not allow for the turnover of nitrogen via the roots. Estimates of the root : shoot ratio of *A. vesicaria* in arid zone communities vary from 50:1 (Cowling, 1969) to 0.21:1 (Jones & Hodgkinson 1969), and no estimates of the root turnover in Australian arid zone communities are known. Root turnover has been omitted from the model for reasons described below.

6.441 *The nitrogen model*

On the basis of the above data, and especially the theses of Correll (1967) and Cowling (1969), the nitrogen supply is modelled as outlined in figure 6.6. Mineralization takes place only when the top soil layer is moist; here taken to be any day in which more than 1 mm of rain fell or in which the soil moisture of the top zone was greater than 18 mm. Mineralization takes place at a constant rate of 0.4 kg ha^{-1} day^{-1} which is equivalent to the lower rates recorded in mineralization experiments in the laboratory. During growth *A. vesicaria* takes up 0.023 kg of nitrogen per 1.0 kg of leaf biomass increment, *K. sedifolia* takes up 0.080 kg per kg, and the ephemerals 0.015 kg per kg (table 6.1). These rates are possibly too high for the perennials since they do not take into account the observation that *A. vesicaria* conserves nitrogen by withdrawing it from the leaves before they are shed. Charley & Cowling (1968) showed that the leaf litter under an *A vesicaria* bush had a nitrogen content of 0.6% whereas the nitrogen content of the leaves on the bush was 1.9%. However, any reduction in uptake would be balanced by a reduction in the nitrogen content of the litter fall, so this factor is not of critical importance in this model.

The mineralization depletes the soil organic material pool which is in turn fed by soil surface litter breakdown. Both of these pools are calculated in terms of kg ha^{-1} of nitrogen. The rate of breakdown of litter and the return of nitrogen to the soil is unknown. Litter biomasses ranging from 10 kg ha^{-1} to 560 kg ha^{-1} were measured on Middleback Station, and although it is recognised that these figures represent only the approximate range of values, they imply a rapid breakdown of litter biomass. It is possible that the rate of nitrogen return is more rapid than the return of biomass as a whole, hence litter biomasses are only an approximate guide to the rate of nitrogen return. The approximate decay rate can be calculated by assuming the rate to be constant, r and also that the rate of litter fall is constant, L. The litter pool, P will be of such a size, that losses from the pool equal the input rate,

(E6.10) $r\ P = L$ or $r = L/P$,

where L is 13 kg ha^{-1} yr^{-1} or 0.036 kg ha^{-1} day^{-1}, and if the nitrogen content of the litter is assumed to be 0.6% (Charley & Cowling, 1968), then the mean decay rate at Middleback varies from,

$$r = 0.036 / (10. * 0.006) = 0.60$$

to,

$$r = 0.36 / (560 * 0.006) = 0.011.$$

These rates represent half lives of nitrogen in the litter of 1 day and 64 days respectively which is a surprisingly rapid turnover. Even at the slower rate, only 2% of the nitrogen in the litter fall would be present in the litter after 365 days. This is similar to the results of Beadle (reported in Charley, 1972) for *A. vesicaria* litter.

The slower rate is incorporated into the model, although too much reliance should not be placed on the size of the resultant litter pool. The rate of return of nitrogen from the litter to the soil, would vary with the weather conditions, and also a large amount of litter is removed by wind or water to concentrations in creeks, watercourses and fence lines. Ants have also been observed taking grass litter and saltbush leaves down their holes.

If the root nitrogen turnover had been considered in the model, this would have effectively increased the uptake of nitrogen per gram of leaf produced since the additional root biomass would have had to be allowed for. However new root growth would usually precede new leaf growth and also there is no reason to expect that root production and leaf production would be correlated. It is known (Cowling, 1969) that *A. vesicaria* produces many fine roots in each major wetting cycle and that these die off during even a short dry period, however Jones & Hodgkinson (1969) considered that root production was only a minor part of total *A. vesicaria* production. Also, the nitrogen incorporated into the roots does not pass through the same decomposer chain as does the above ground litter. Being already in the soil, and much of it in the form of very fine roots, the decomposition is probably very rapid on the next wetting. It was therefore decided to omit the root nitrogen turnover.

This model also omits the nitrogen fixation process, and the possible input of nitrogen via rainfall. Beadle & Tchan (1955) estimated that nitrogen fixation added up to 3.0 kg ha^{-1} yr^{-1} to the soil, which is a significant amount compared to the 13.5 kg ha^{-1} yr^{-1} of nitrogen turnover. However little is known about the dynamics of the process, nor is its opposite counterpart, denitrification, understood. The net nitrogen gains and losses would be important in long term studies of grazing systems, where nitrogen losses from exported animal products and erosional losses would become significant.

It should be noted that the growth model has a de facto input of nitrogen from the germination model. The ephemerals do not draw their nitrogen from the nitrogen pool during their seedling stage, but are assumed to take it from their seeds. This amounts to a mean input of 1.6 kg ha^{-1} yr^{-1}, and could be counteracted by a continuous loss from the plants, or by a more discrete loss at the time of flowering.

The redistribution of nitrogen throughout the paddock via sheep urine and faeces is discussed in section 10.11.

6.45 *Plant competition*

Plant competition is another field that has been well studied in agronomic crops and more temperate grasslands, and very little so in the arid zone. The topic has been adequately reviewed by Milthorpe (1961), Donald (1963) and Risser (1969). The plant competition function in the model is included partly to account for the competition for soil moisture supplies, a factor otherwise omitted.

Many different mathematical functions have been proposed as competition factors but in the model the simple logistic growth function is used (DeWit, 1961). This function has been found to be applicable to some experiments where plants are competing for space, or some factor associated with that space, such as soil moisture. The function is,

$$(E6.11) \qquad f = (B_x - B) / B_x$$

where B_x is the maximum biomass. Two competition functions were used in the model, one for the ephemerals and one for the perennials. It is assumed that the ephemerals and perennials do not directly compete for the nutrients accounted for by this factor. The maximum ephemeral and perennial biomasses are both set as 1500 kg ha^{-1} since this was approximately the highest biomass observed at Middleback or in K.V.R. in each case.

It is recognised that these competition functions are probably incorrect and possibly misleading in their effect in the model. It is assumed that competition occurs during the growth period and has maximum effect at the maximum growth rate, but Anderson et al. (1969) have argued that the spacing of *A. vesicaria* bushes is determined by differential mortality in the size classes during water stress periods. Mott & McComb (1974) have pointed out that a positive association between ephemerals and individual shrubs is common in Australia, and at a Western Australian site they attribute this to increased water storage and nitrogen availability in the mounds around shrubs. No similar association has been observed at either K.V.R. or Middleback, but nevertheless there may be other types of ephemeral-shrub interactions that have been omitted from the model.

6.5 *Validation*

For the reasons discussed in section 6.2, emphasis in validating the growth model was placed on long term runs of several decades, rather than on accurate fits to seasonal data. The K.V.R. perennial and ephemeral biomasses as estimated in section 6.3 were used for both fitting and validating the model. The model was run using the Koonamore Station daily rainfall data for the years 1926 to 1974[1]. The daily mean temperature was assumed to follow an annual sinusoidal function, estimated from records made at K.V.R. from 1927 to 1931. The daily mean temperatures recorded during this short period are 1 to 2°C higher than those for Yunta (60 km south of K.V.R.) for a 15 year period. This difference is consistent throughout the year, so the K.V.R. records were assumed to be an adequate estimate of the annual temperature cycle at the reserve. The daily evaporation rates were estimated from the monthly mean values as in section 5.453.

During the runs used to fit the growth model, only the years 1926 to 1951 were estimated. The model simulated a saltbush steppe site and included the species *S. nitida*, bassia and *A. vesicaria*. *K. sedifolia* was not included since there was no suitable validation data. The initial conditions were set arbitrarily at an *A. vesicaria* biomass of 700 kg ha^{-1} and no ephemerals in 1926. It was found that initial *A. vesicaria* biomasses in the range 200 to 700 kg ha^{-1} had little effect on the shape of the model output after the first few years.

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[1]: Commonwealth Bureau of Meteorology, Rainfall Records: Koonamore Station 1884 to 1968. Australian Archives, AP564, series 5, Box 188.

Rainfall records were available from 1884, but it was not valid to run the model from an earlier date since the reserve had been subjected to heavy grazing until mid 1925.

The programs were written so that the model could be run in either interactive or batch mode with parameter changes made by NAMELIST statements before each run. The model was first run using the best estimates of the parameters available in the literature. The output was compared by eye to the graph of the biomass changes with time as derived in section 6.32 and 6.33. The type of parameter correction needed was usually obvious from the comparison of the real and simulated biomasses, and no systematic approach to parameter fitting was used. In general, those parameters which had some basis in the literature or other studies were varied as little as possible. It was found that the model was very sensitive to competition for nutrients, and especially so for the ephemerals. The period of germination and establishment was the most critical time. If one taxon gained dominance at this point then it could exclude the other taxon for the rest of the growth phase and dieback period.

Over 120 runs of 26 years were used in obtaining the final model. The model was then run for the period 1926 to mid 1974, and the extended run compared with the K.V.R. data. This represents a partial validation of a model for this site, although it by no means validates its use elsewhere.

Differences between the model and the K.V.R.

observations can occur due to inadequacies in the model, different rainfall events at the homestead and reserve, (8 km apart) or extreme temperature conditions. The early meteorological records indicated that thunderstorms were common in the Koonamore area, especially in summer and autumn. These can result in very localized, heavy falls, possibly leading to localized vegetation responses.

Figure 6.9 compares the simulated and observed changes in ephemeral biomass for the period 1926 to 1974. The ephemeral biomasses are based mainly on the photographs of quadrat 100, since this was the most complete series. They are in good agreement, with the main exception being the 1942 - 1943 period. All versions of the model produced in ephemeral input in this period even though none appeared in the photographs. Notes taken when the quadrats were charted in 1942 and 1943 indicated that a small amount of ephemeral germination did occur in each of those years. It was possible that rabbits may have been very common in the reserve at the time. However it is unlikely that they had any major effect on the vegetation since the photographs of quadrat 100 show some undamaged young *Cassia sturtii* bushes even though this species is known to be very susceptable to rabbit damage (Hall et al., 1964). A close examination of the rainfall and soil moisture budgets indicates that the growth shown in the model is due in a large part to a fall of 121 pt (31 mm) on one day in February 1943. It appears likely that the discrepency between the model and the observed response is due to this localized rainfall that missed the reserve.

In figure 6.9 the model output does not show a response to the favourable conditions in 1950 as was observed in the reserve. A more detailed examination of the model showed that a grass growth occurred in 1950, but after August 31st. This could be due to an inadequacy in the model or to an unusually warm winter at Koonamore.

It is little use extending this type of comparison of the model output and the observed results, given the many possible sources of error and the difficulty in attributing them to the model or the driving variables. In summary, the model was fitted to reproduce all but one of the major peaks in the ephemeral biomass from 1928 to 1950, and produced only one other peak not observed at K.V.R. The observed decline in the size of the 1931, 1939 and 1946 peaks was also simulated by the model, although the relative sizes of the peaks of the 1950's was not simulated so well. The dominant species at each biomass peak as estimated from the photograph, were in good agreement with the modelled biomass (table 6.2).

The agreement between *A. vesicaria* observed at K.V.R. and the model results is better than that for the ephemerals (fig. 6.10). Almost every peak and trough from 1927 to 1970 match, with the small peak observed on the reserve in 1934 being the only exception. The model output shows a slow decline in biomass from 1926 to the 1940's, whereas the K.V.R. records indicate a general increase. This is to be expected since the reserve was recovering from heavy grazing. The model also showed an increasing biomass when it was started with a low 1926 biomass.

The 1942 and 1950 discrepencies observed in the ephemeral comparisons are not as great in the case of the perennials. This further indicates that the source of the discrepencies is likely to be due to isolated events with a short term effect such as summer rainfalls, or extreme temperature conditions. These would affect ephemeral, more than perennial species.

At this stage the model was expanded to include *K. sedifolia*. There was little published information on which to base the model so some rather arbitrary assumptions had to be made. It was assumed that *K. sedifolia* is a slower growing bush than *A. vesicaria*, with a greater resistance to drought, and therefore a slower die back rate. *K. sedifolia* was also assumed to be able to draw on water from zone 3 of the soil moisture model. Growth could occur only when water was available in zone 1 and zone 2 or 3, while dieback occurred only when no water was available in any of the zones. The effect of temperature on growth was assumed to be a simple hyperbolic function as summarized in figure 6.7.

The model was run with the rainfall and temperature models used in the complete grazing model. These models are based on Middleback data rather than Koonamore, so it was envisaged that there may have been significant differences in the balance of the competing species and in the long term stability of perennial biomass. Several runs of 50 years were done and the results indicated that both ephemeral species behaved in a manner similar to the runs with Koonamore data. The range of biomasses achieved was the same, and either species was able to achieve dominance depending on the conditions.

The perennial species showed a tendancy to increase in biomass even after the *K. sedifolia* data had been fitted to achieve approximate stability. This increase also occurred if the model was run using the Middleback data and with only *A. vesicaria* present. To investigate this aspect of the model further a series of runs starting with different initial perennial biomasses were carried out. Each run included six, 10 year simulations using independent driving variables, but with the same set of driving variables used for each set of different initial conditions. This is equivalent to a trial including a number of plots with different initial biomasses, run in parallel for six, 10 year periods. The annual exponential growth rate, k, as discussed in section 6.2, was estimated by plotting ln (biomass) against time and calculating the slope. Again biomasses on August 31st of each year were used. The results are summarized in table 6.3.

No detailed statistical treatment was attempted since all that was needed was an estimate of the biomasses at which approximate stability occurred. Stability was defined by arguing that at certain sets of initial conditions the biomass would be as likely to show an increase as a decrease in 10 years. The results indicated that this occurred when the total perennial biomass was about 1000 to 1100 kg/ha. This conclusion was supported by the estimates of the mean annual growth rates estimated over each of the 10 year growing periods and the mean biomass after 10 years expressed as a percentage of the original.

The value for stable biomass appears to be too high when compared with the information available about biomasses at Middleback. For example, the mean biomass in Wertigo paddock based on 37 sites in October 1972 section 4.1), was 163 kg ha^{-1} of *A. vesicaria* and 214 kg ha^{-1} of *K. sedifolia*. A biomass estimate in October 1973 based on 13 of the 37 sites gave similar results. In some of the sites the total perennial biomass was 700 kg ha^{-1} and in some specially chosen quadrats, perennial biomasses as high as 1200 kg ha^{-1} were recorded in October 1973.

The growth model produces higher biomasses when it is run with Middleback climate variables, than with those for Koonamore. This is not unexpected since Middleback has a higher mean annual rainfall, lower evaporation rates and a less extreme temperature range. Thus, it may be argued that the model cannot be applied to the Middleback area. However, since there is no alternative data, I have been obliged to use this model, albeit with caution. Three options were available in incorporating the growth model into the grazing model. The model could be refitted for the Middleback area by adjusting parameters so that it achieved stability as defined above, but with lower perennial biomasses. This was not done since further fitting may have worsened the demonstrated ability of the model to describe the K.V.R. data. Further parallel fitting to both the K.V.R. data and the Middleback biomass estimates was potentially too time consuming to be justified.

The second alternative, was to run the grazing model with initial biomass conditions similar to those observed to lead to stability. This was rejected since it would have increased the potential animal productivity of the paddock due to the higher plant production. It was also not clear whether biomasses of about 1100 kg ha^{-1} were actually achievable in a grazed paddock like Wertigo. It was possible that the biomasses were being held at a reduced level due to grazing effect. Therefore it was decided to use observed Wertigo biomass values as initial values in the grazing model, but to recognise that there could be a strong upward trend in biomass in long runs. This effect would be reduced by making all comparisons of sensitivity of the model to various parameters or of the effect of different management schemes, on the same set of climatic data. It was not possible to carry out a series of long runs of the complete grazing model in order to determine the magnitude of any such long term trends, due to the computing time involved.

6.6 *Conclusions*

The growth model described above, is incorporated into the complete grazing model and is used for each of the 37 cells. The growth processes in each cell are independent of the other cells, but they interact via the soil moisture, and sheep grazing and behaviour models.

Probably the most important aspect of this section of my project, is the examination of the K.V.R. photographs. This study produced one of the longest sets of biomass data available for an arid zone site, although the method was indirect and not fully quantitative. It does show the value of photographic records in long term studies. Photographs are easy to collect compared to quadrat charting or biomass estimation, and with the use of stereo pairs, colour, false colour and other improvements, the amount of data available from them would be increased even more.

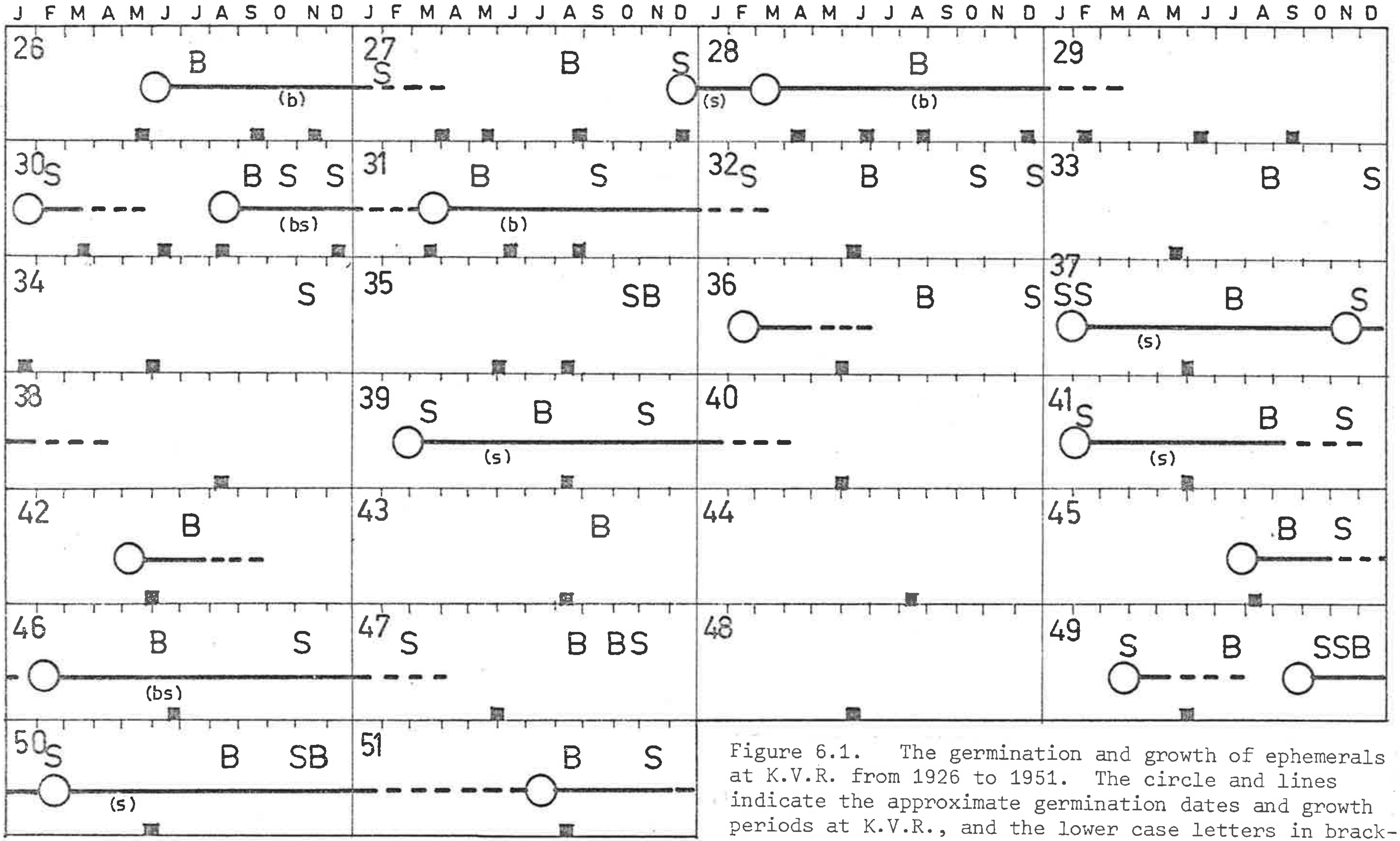


Figure 6.1. The germination and growth of ephemerals at K.V.R. from 1926 to 1951. The circle and lines indicate the approximate germination dates and growth periods at K.V.R., and the lower case letters in brackets indicate the dominant taxa. The capital letters above the line are the germination events simulated by the germination model. The solid blocks indicate the dates at which photographs were taken.

B, b ... bassias and other ephemerals.

S, s ... *Stipa nitida* and other grasses.

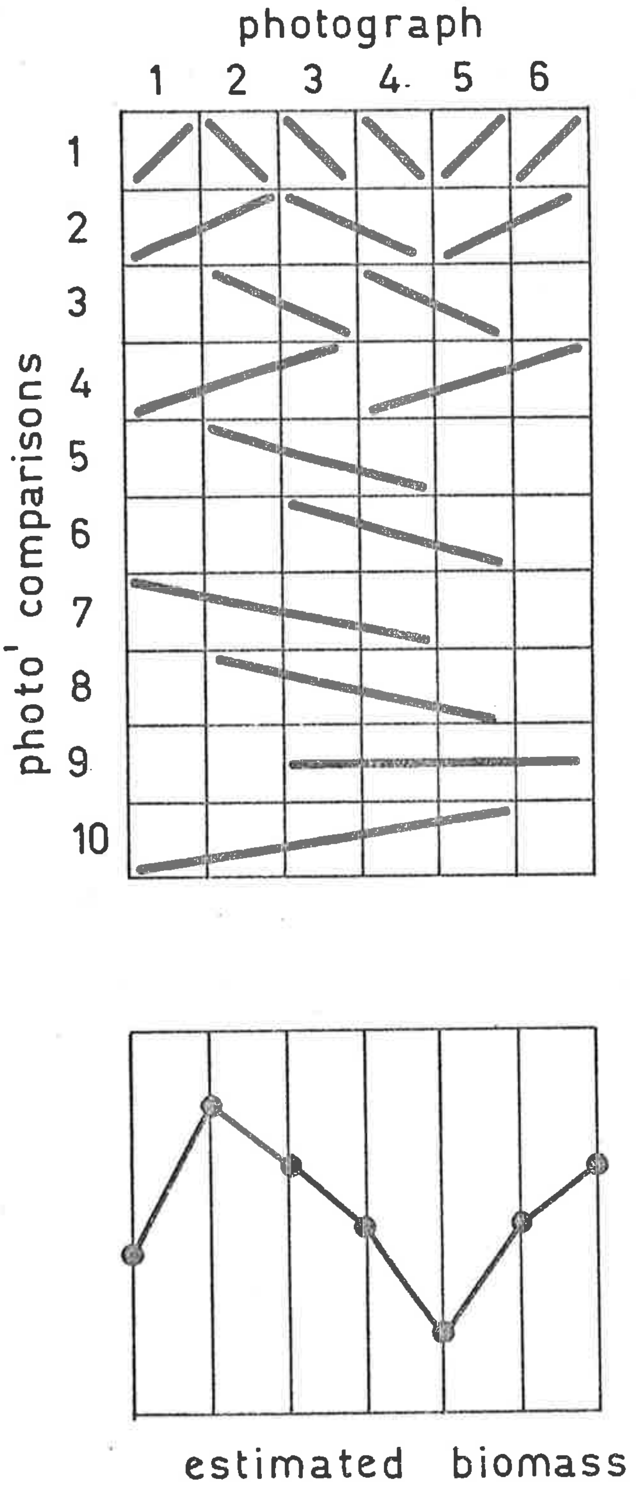
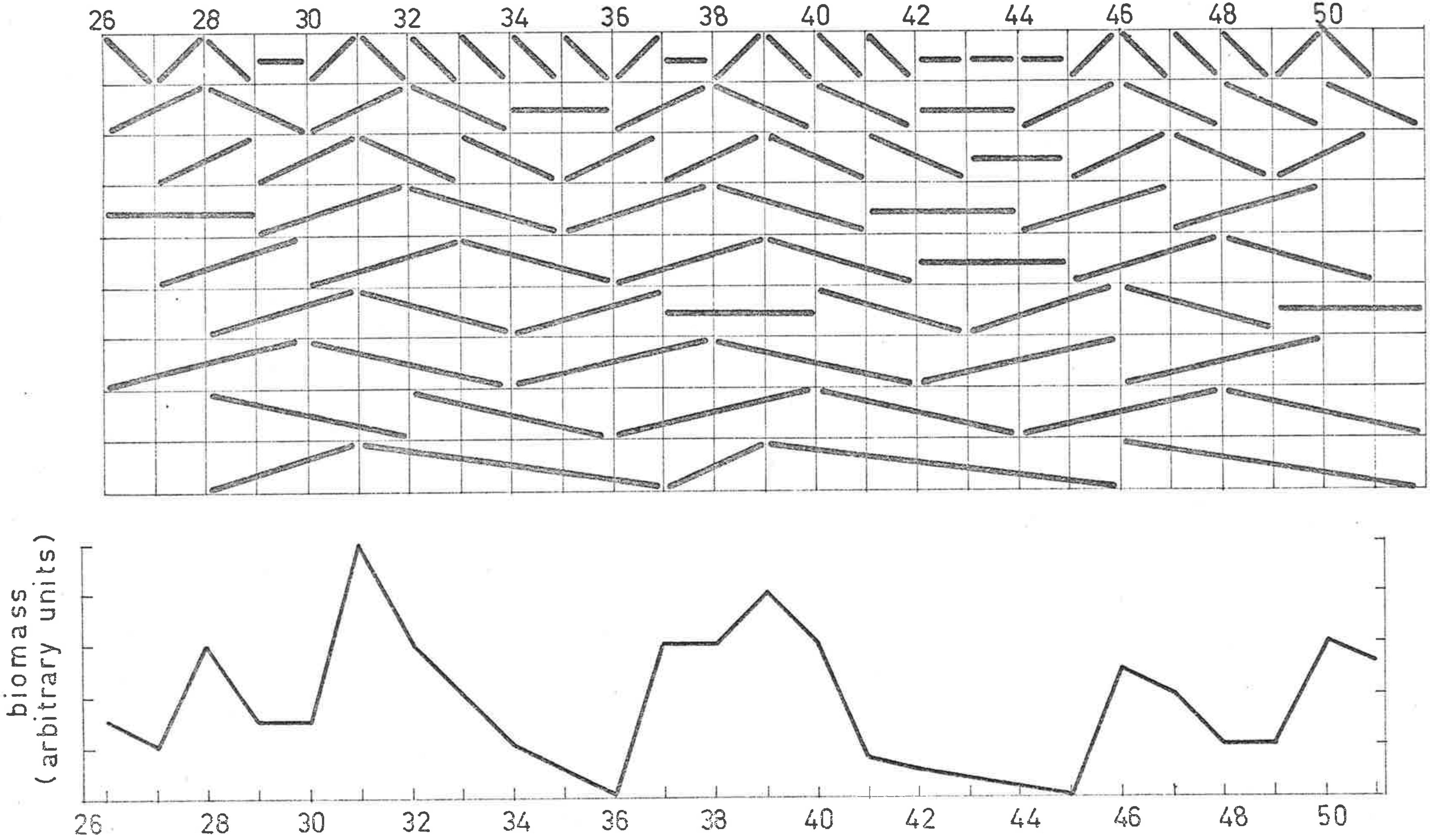


Fig. 6.2. An example of the method used to determine the biomass dynamics in K.V.R. from the photographic record. A full explanation is included in section 6.32.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40
42
44
46
48
50
biomass
(arbitrary units)
26
28
30
32
34
36
38
40
42
44
46
48
50

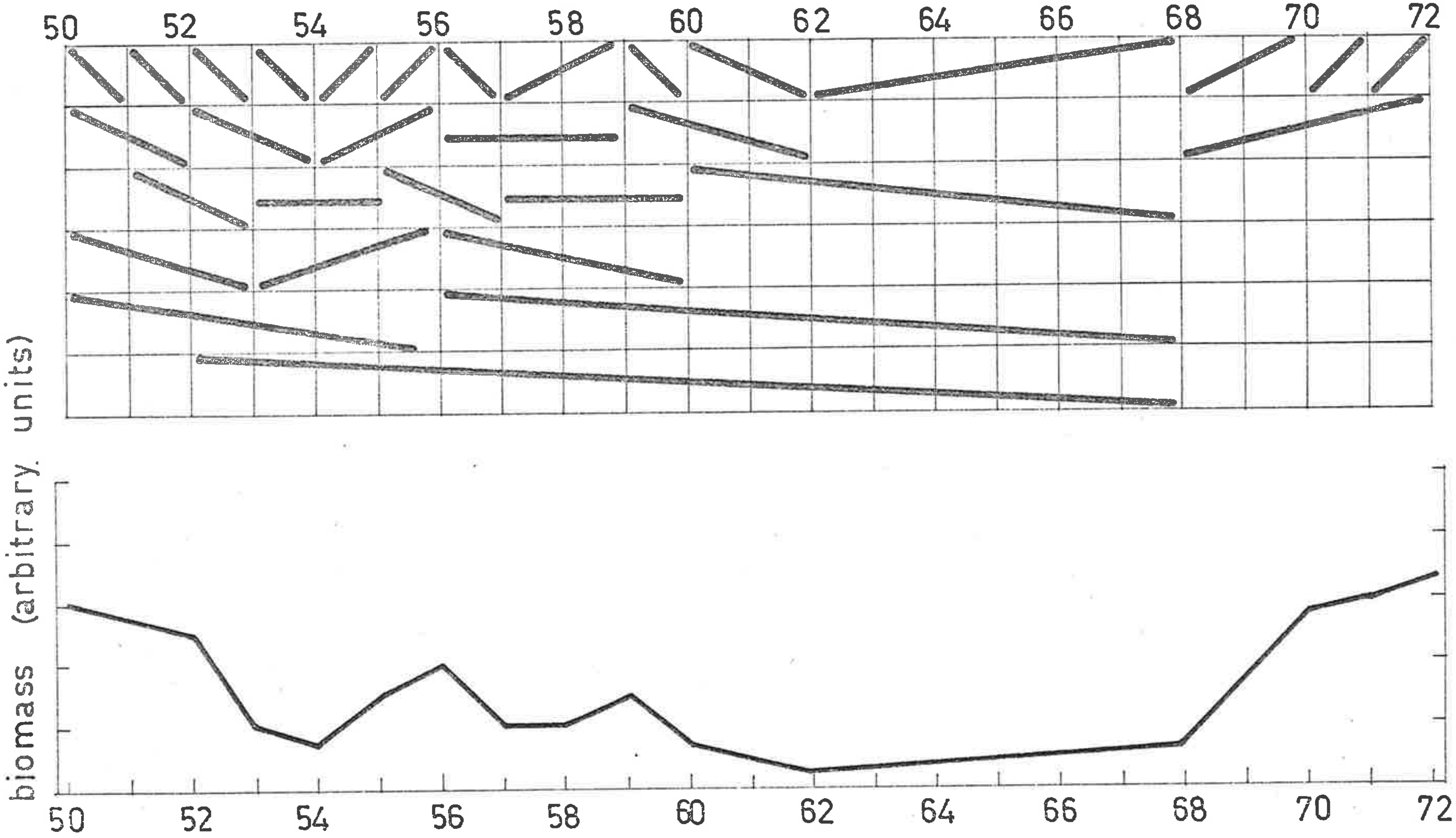


Fig. 6.3b. The estimated ephemeral biomass in quadrat 10A on K.V.R. from 1950 - 1972. See section 6.32.

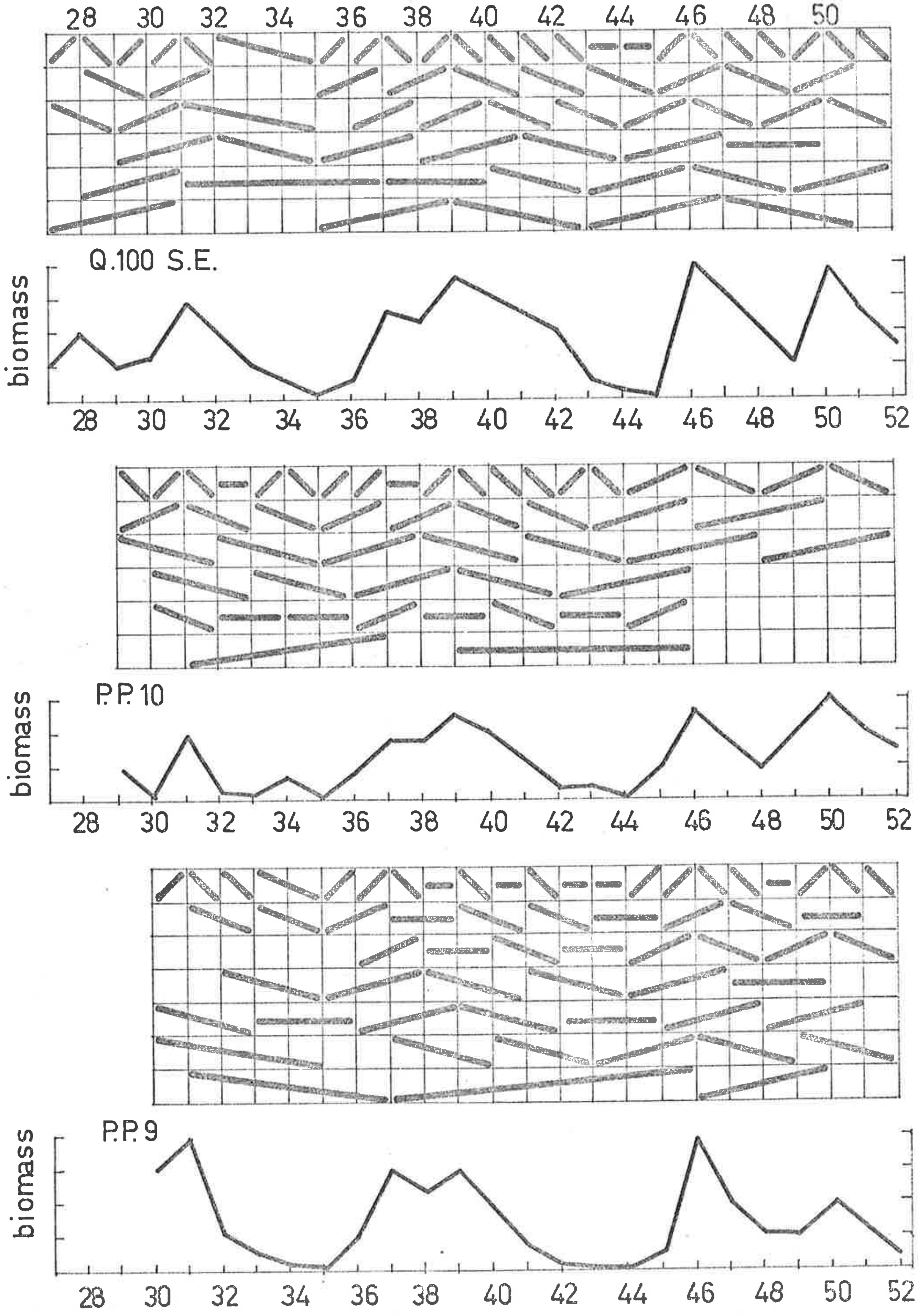


Fig. 6.4. The estimated ephemeral biomasses in some other quadrats on K.V.R. See section 6.32.

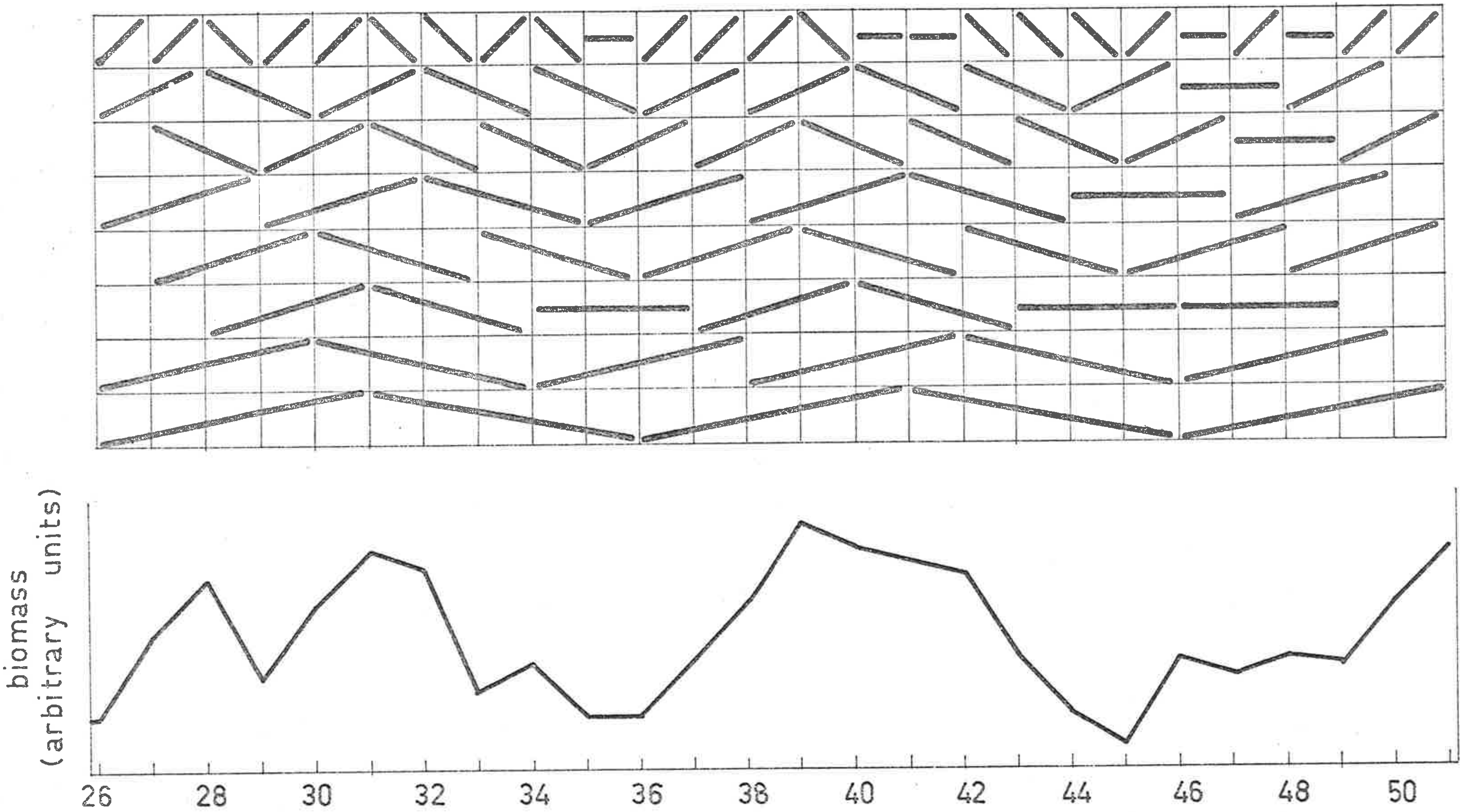


Fig. 6.5a. The estimated perennial biomass in quadrat 10A on K.V.R. from 1926 to 1950. See section 6.33.

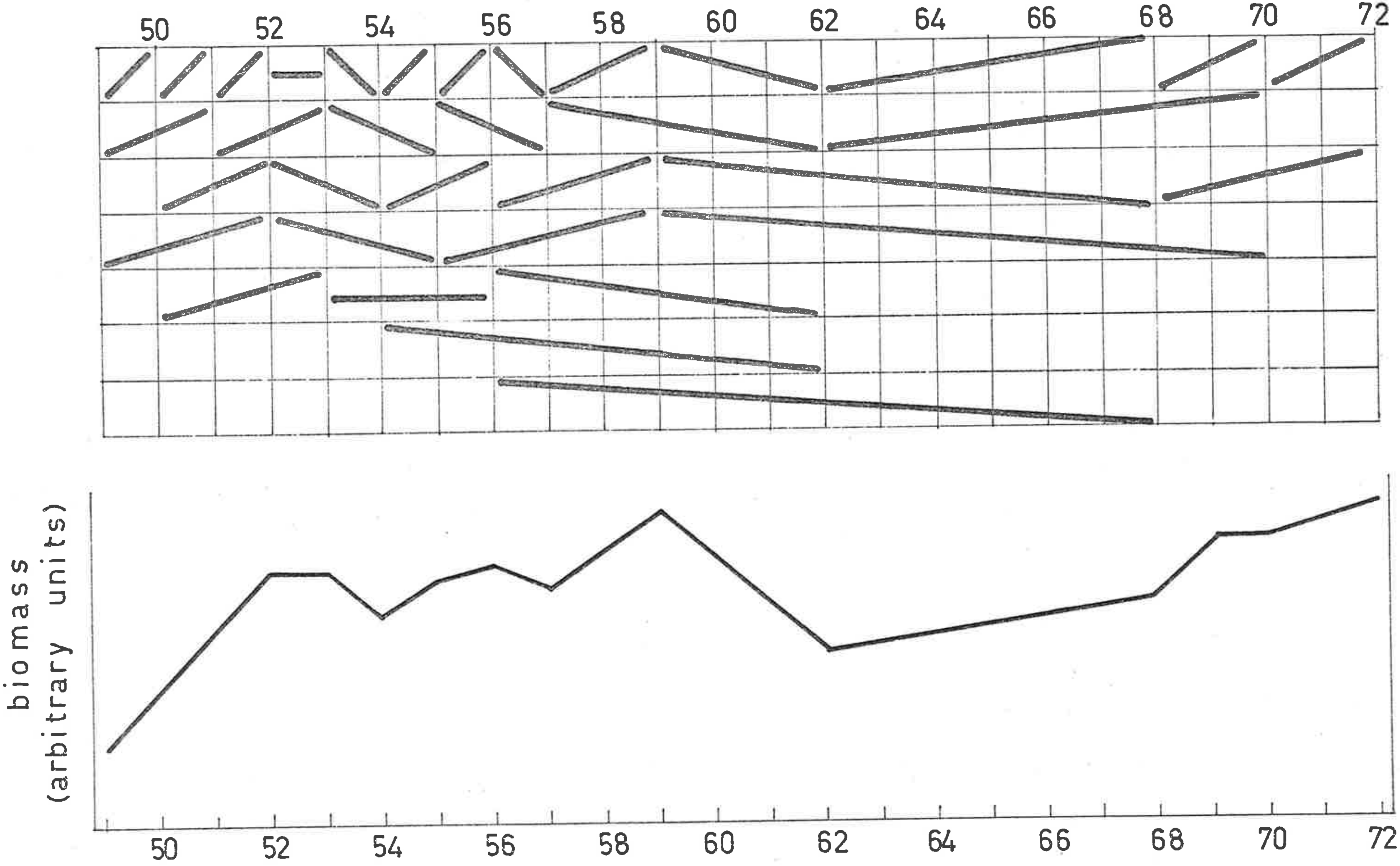


Fig. 6.5b. The estimated perennial biomass in quadrat 10A on K.V.R. from 1949 to 1972. See section 6.33.

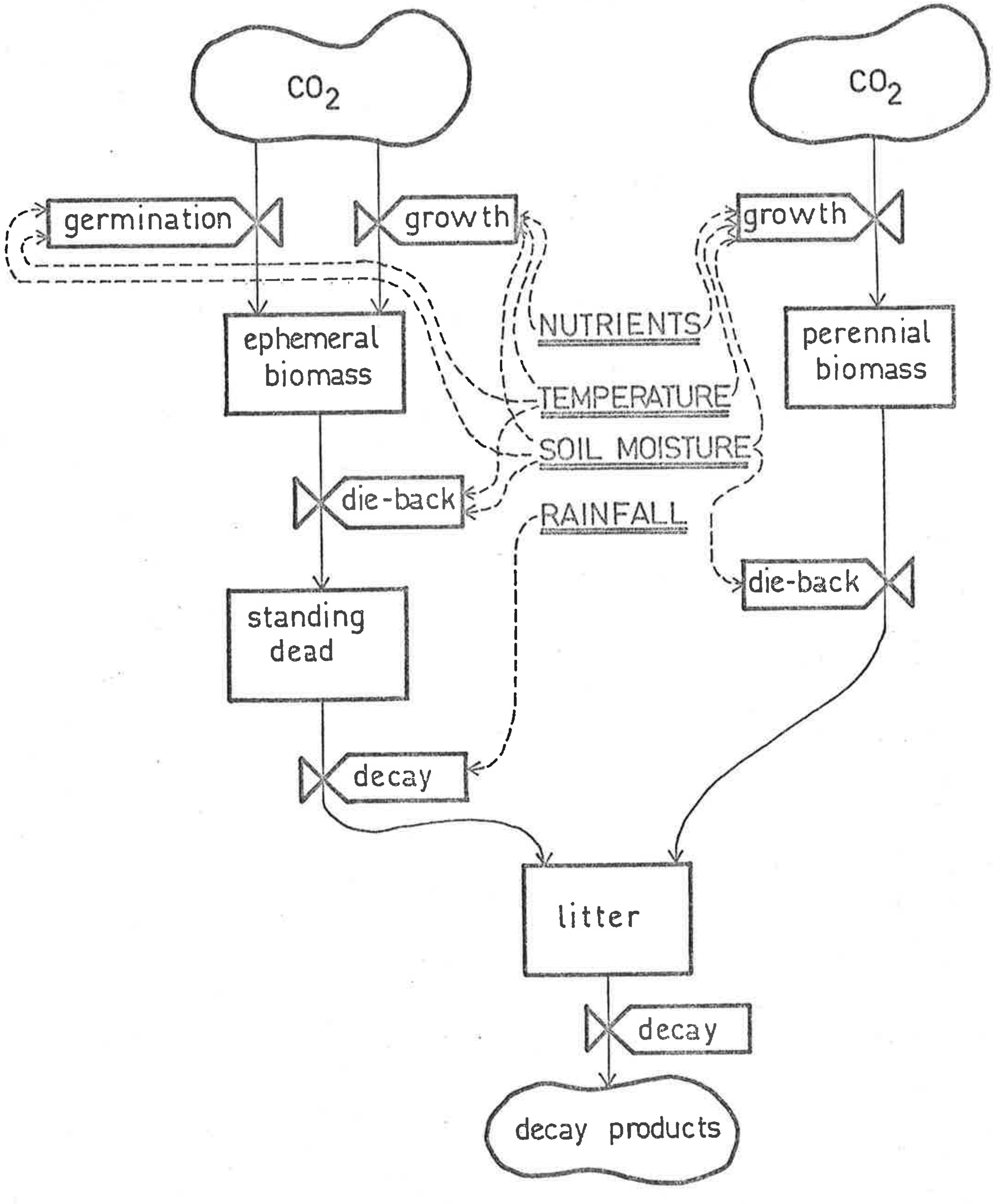


Fig. 6.6a. A flow chart of the growth model. Solid lines represent the flow of organic matter and dashed lines the flow of information.

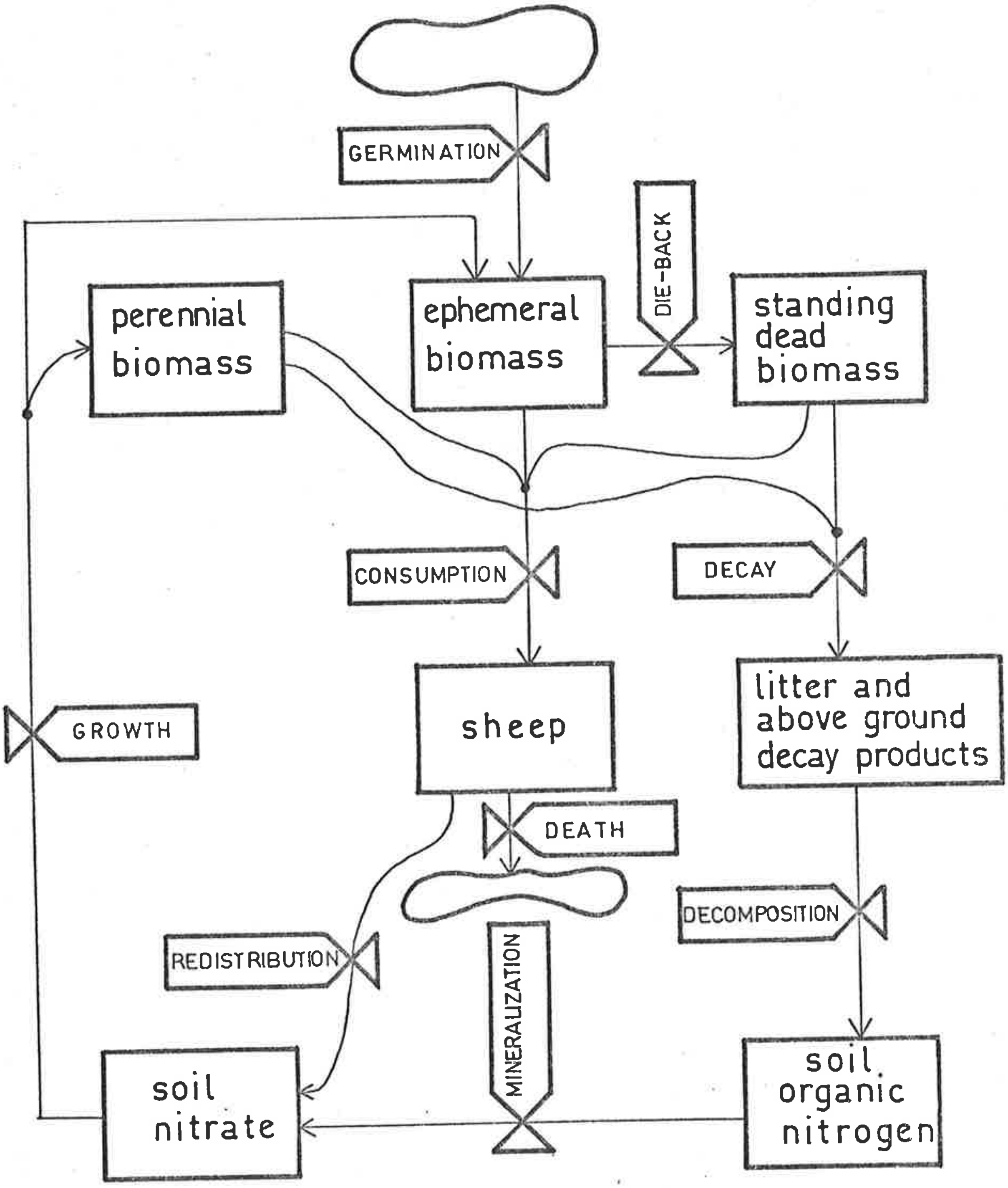


Fig. 6.6b. The flow of nitrogen in the growth model. The major flow is around the outer cycle, but as discussed in section 6.44 there is a small source and sink due to the incomplete modelling of seed distribution and sheep carcass decay.

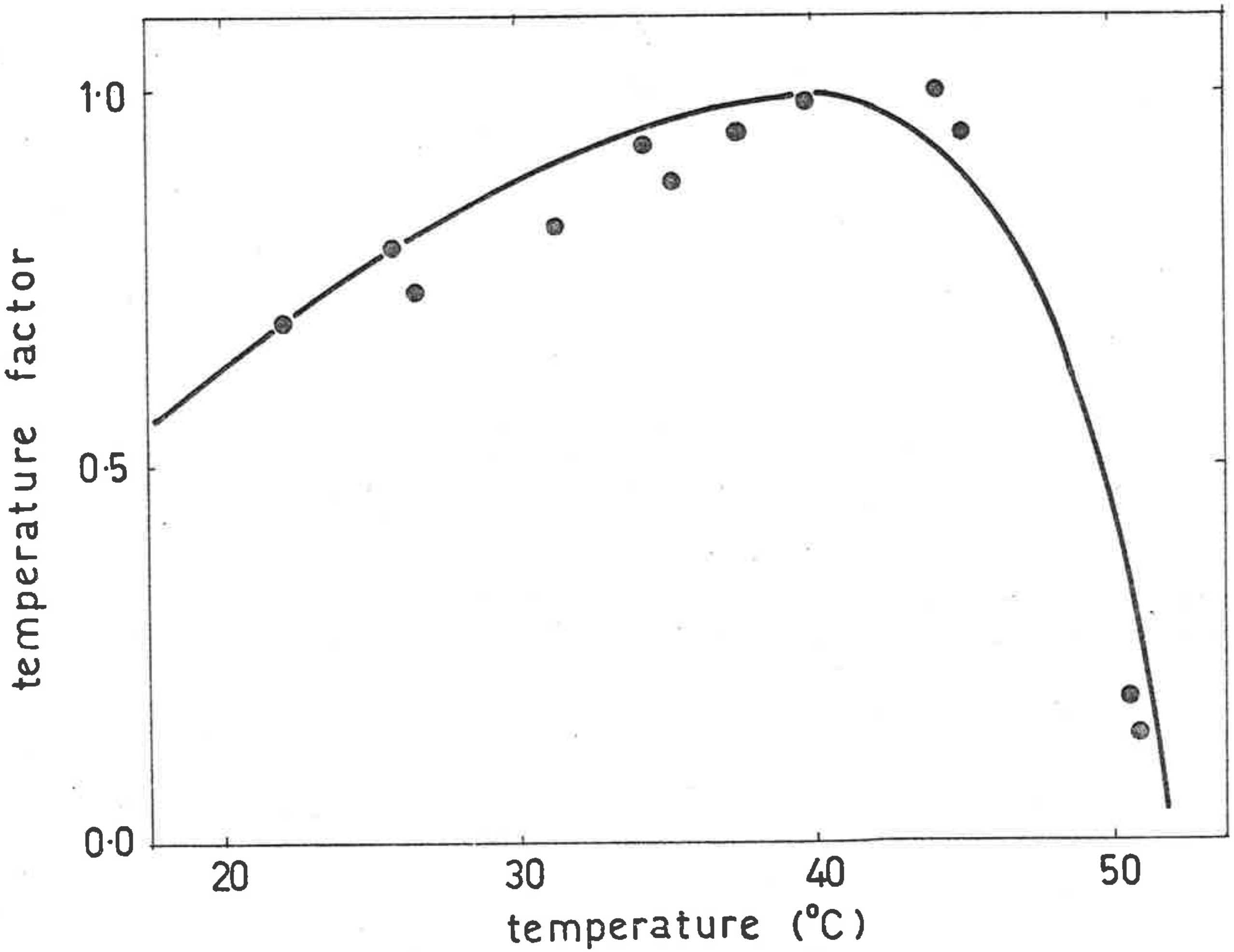


Fig. 6.7a. The temperature factor for the growth rate of *Atriplex vesicaria*,

$$F = (0.166 - 0.0206 * T + 8.245/[T - 59])/0.58.$$

Based on the data of Hofstra & Hesketh (1969).

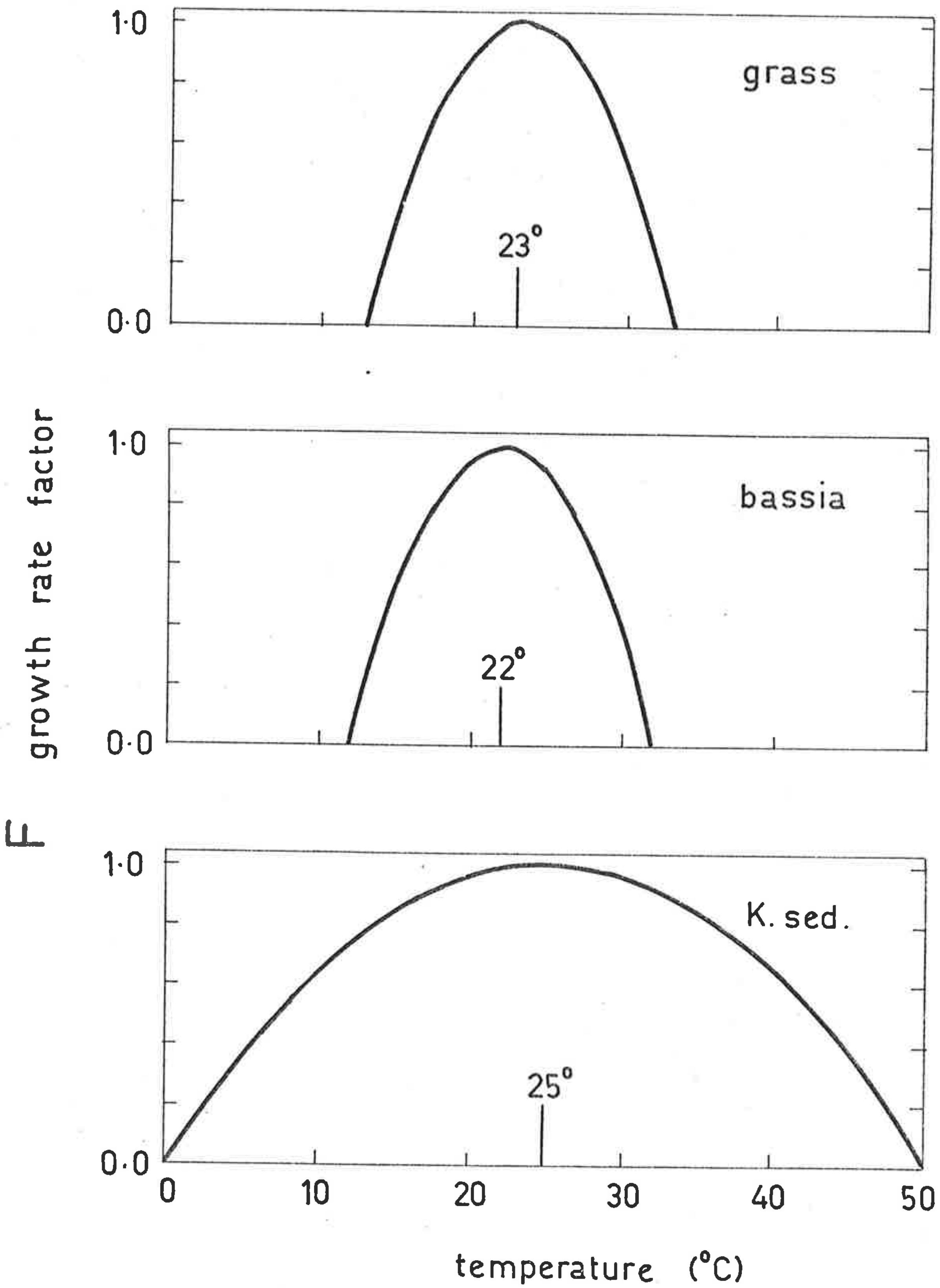


Fig. 6.7b. The temperature factor for the growth rates of the above species. All the curves are of the form, $F = 1.0 - a * (b - T)^2$, where a and b are constants and T is the mean day time temperature.

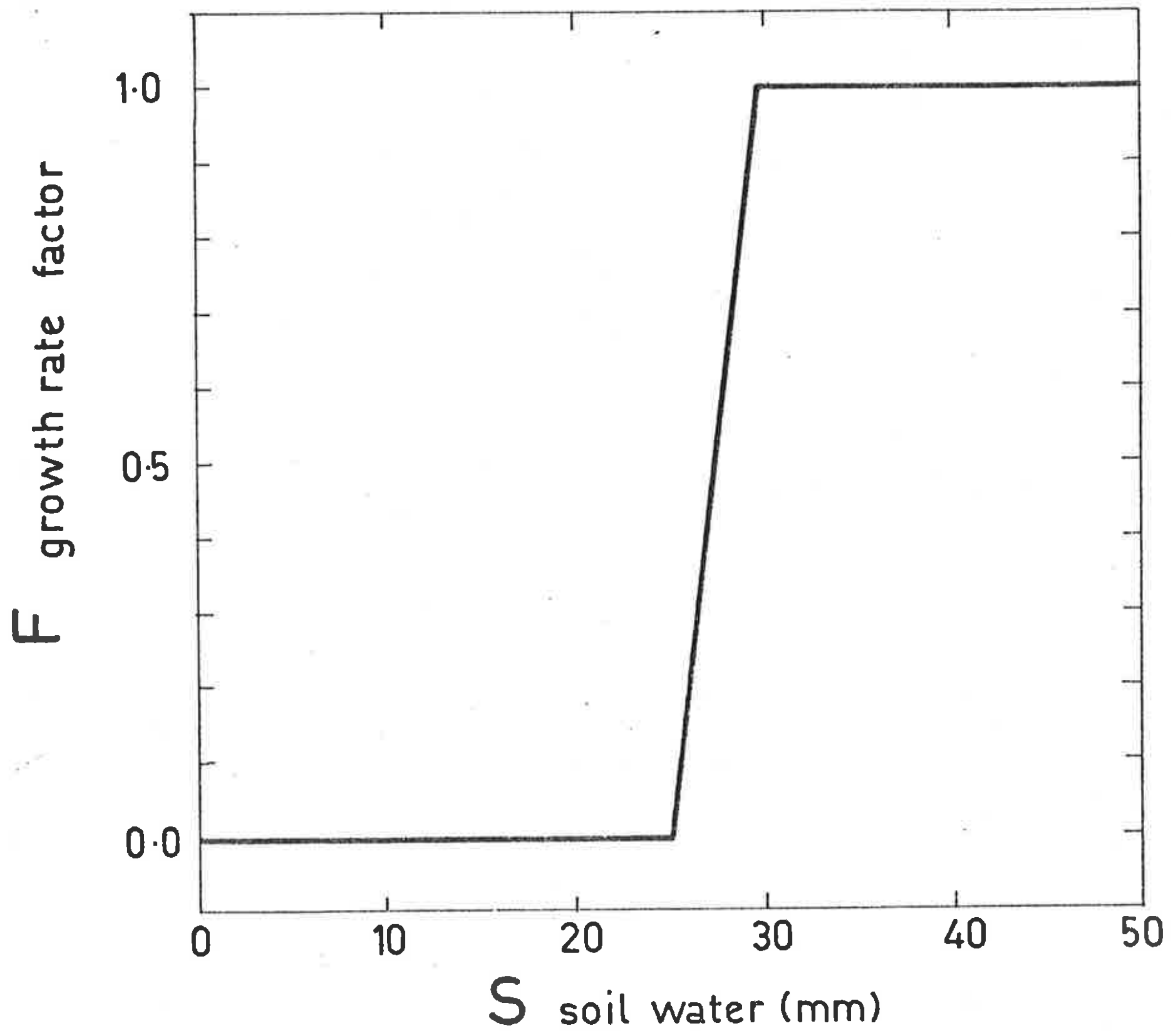


Fig. 6.8. The effect of soil water content on the growth rate of the perennials. For *A. vesicaria* 'soil water' is the soil moisture content of zone 2, while for *K. sedifolia* it is the average soil moisture content in zones 2 and 3.

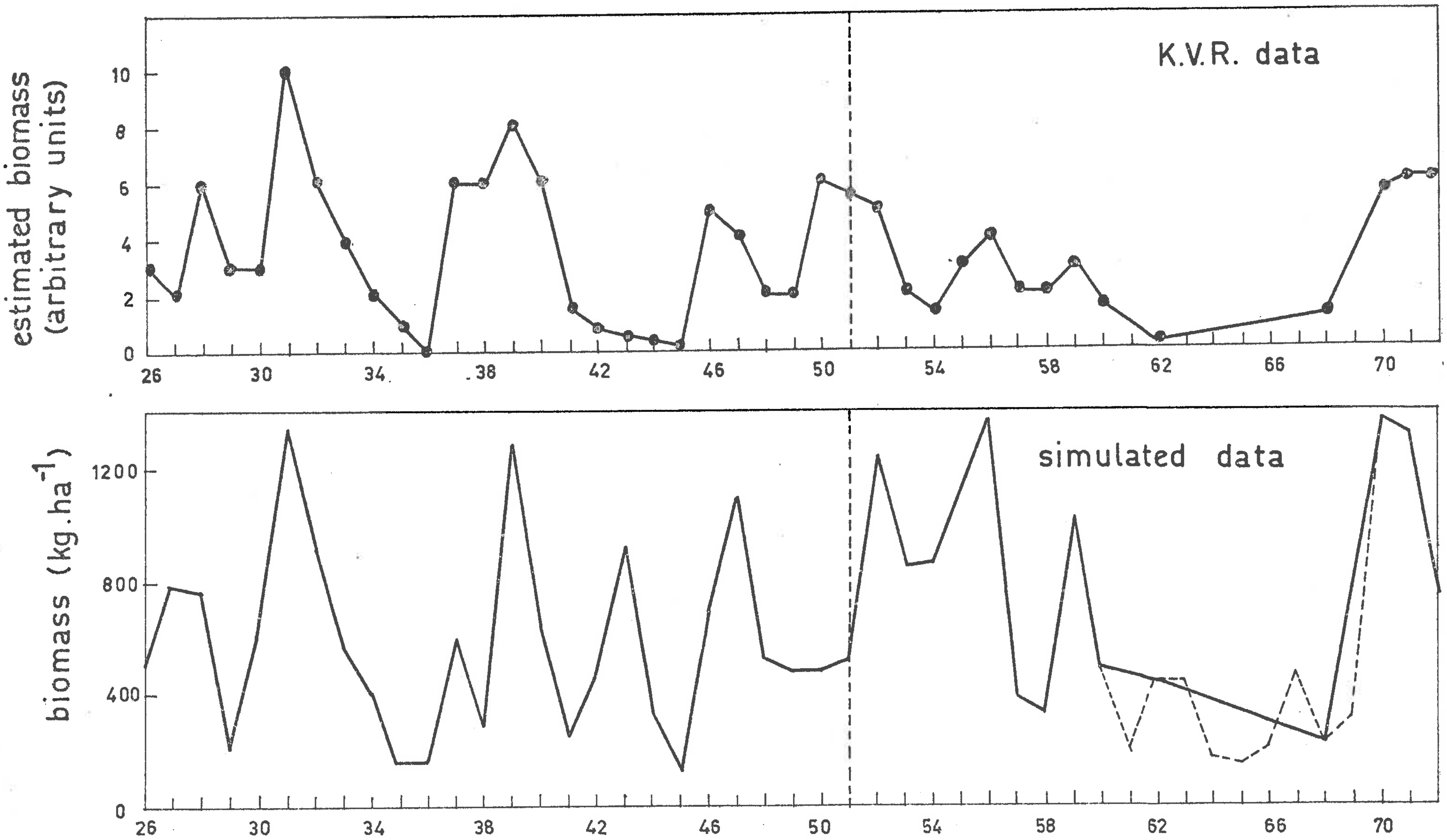


Fig. 6.9. A comparison of the ephemeral biomasses as estimated from the K.V.R. data, and the biomasses predicted by a run of the model using the Koonamore rainfall data. The data to the left of the dashed line were used for fitting the model, and the data to the right were used as partial validation.

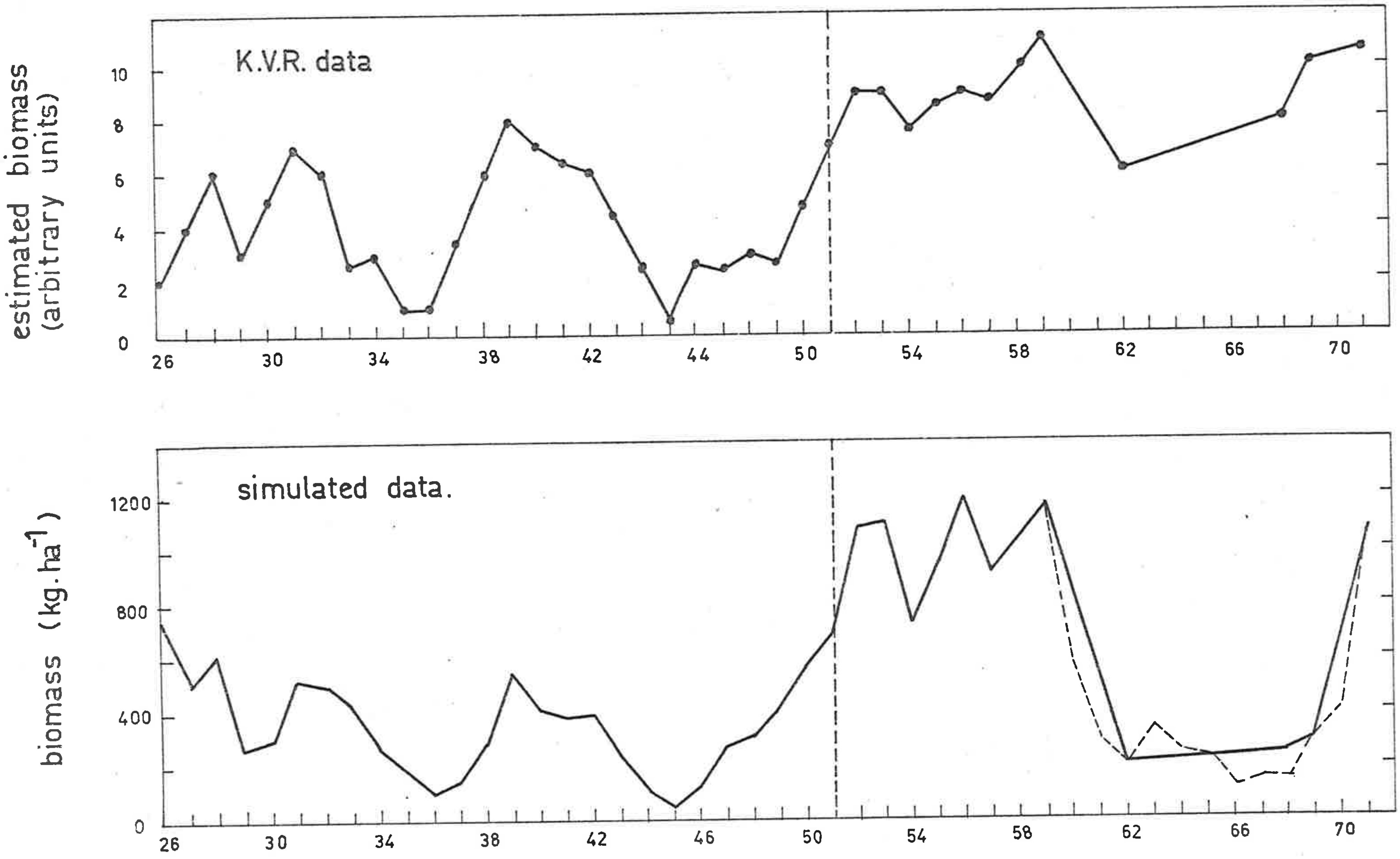


Fig. 6.10. A comparison of the perennial biomasses as estimated from the K.V.R. data, and the biomasses predicted by a run of the model using the Koonamore rainfall data.

Nitrogen contents of major species

	leaf N* %	wood N* %	ratio** leaf:wood	kg N per kg of leaf
Atriplex vesicaria	1.25	0.52	1 : 2	0.023
Kochia sedifolia	2.21	1.44	1 : 3	0.065
ephemerals	1.50	-	-	0.015

	leaf** biomass kg ha^{-1}	wood biomass kg ha^{-1}	total N kg ha^{-1}
Atriplex vesicaria	163	330	4.0
Kochia sedifolia	214	640	14.0
			18.0

Allow ⅓ turn-over per year:

= 6.0 kg ha^{-1} $year^{-1}$.

Allow an ephemeral turn-over of 500 kg ha^{-1} $year^{-1}$ at an average of 1.5% N:

= 7.5 kg ha^{-1} $year^{-1}$.

Therefore the total above ground nitrogen turn-over is,

= 13.5 kg ha^{-1} $year^{-1}$.

* Correll (1967)

** Noble (Wertigo data, 1972)

Table 6.1. The calculation of the mean above ground turn-over of nitrogen in Wertigo. The nitrogen contents of the major forage species are estimated in the upper table and the turn-over, based on biomass estimates made in Wertigo, are calculated below.

Year	K.V.R.	Model
1928	b B	b B
1931	B (S)	b B (S)
1937	b S	b (B S)
1939	S (B)	S
1943	-	S s
1946-47	B S	S
1950	S	S
1951-52	s	s
1956	B	S (B)
1959	s (b)	b
1970-71	S	S (B)

Table 6.2. The dominant ephemeral species at K.V.R (based mainly on the Quadrat 100 photographs) and those predicted by the model for the same dates. B and S represent bassia and grass dominants, and the lower case letters refer to the dominance by standing dead material. Pairs of letters represent co-dominance, while brackets indicate that the taxa were present in significant amounts but not dominant.

		Initial biomass *A. vesicaria*/*K. sedifolia* (kg ha^{-1})								
		300/ 200	500/ 300	300/ 500	600/ 400	500/ 500	400/ 600	700/ 500	500/ 700	700/ 700
	Trial									
A. vesicaria	1								↓	↓
	2	↑	↑	↑	↑	↑	↑			
	3	↑								
	4	↑			↓	↓		↓	↓	↓
	5	↑	↑							
	6				↓			↓	↓	↓
mean k (%)		6.1	2.5	1.8	0.4	0.2	0.0	-1.2	-1.5	-2.7
mean biomass		190	131	125	107	105	103	91	88	78
K. sedifolia	1								↓	↓
	2	↑	↑	↑			↑			
	3	↑								
	4	↑	↑							
	5	↑	↑							
	6				↓			↓	↓	↓
mean k (%)		7.0	3.5	2.9	1.5	1.2	1.0	-0.2	-0.6	-1.8
mean biomass		205	144	135	118	115	112	100	96	85

Table 6.3. The results of six trials using the complete growth model. The arrows indicate a significant increase or decrease in *ln* (biomass) over the ten years of each trial. The 'mean k (%)' is the mean annual growth rate calculated as,

$$\text{mean } k = \sum^{6} \frac{ln(B_{10}) - ln(B_0)}{10} \; / \; 6$$

where B_{10} and B_0 are the biomass after 10 years and the initial biomass respectively. The 'mean biomass' is the average biomass after 10 years expressed as a percentage of the initial biomass.

PLANT SELECTION AND CONSUMPTION

7.0 *Introduction*

This chapter deals with the consumption of plants by sheep. It considers both the amount of biomass consumed and the distribution of the consumption among the species. Consumption is important in the grazing model since it is associated with; (1) a loss of plant biomass, (2) the nutrition of the sheep, (3) the growth rate of the plants, since a disproportionate loss of perennating structures usually occurs, and (4) the spatial distribution of biomass and redistribution of nutrients. Only item (1) is dealt with in this chapter.

There has been much confusion in the use of the three terms, selection, preference and palatability. They will not be discussed here, but instead the terms will be used as follows. Selection is a measure of what sheep actually consume while grazing, and thus, is a directly measurable property. Preference is a relative term applicable to a population of individuals of a species. It is usually estimated by ranking the selections of the species, after taking account of their availabilities. Palatability is a property of a species, or more correctly, the individuals of the species. It is difficult to measure directly and is most often inferred from the physical and chemical properties of the plant and its degree of selection (e.g. Jessup, 1951). Preference will change with different mixtures of available forage and also with the satiation of the herbivore. These definitions are in agreement with the majority usage of the terms (see Andrew, unpublished Honours thesis, 1973), although Arnold (1964b) and Heady (1964) discussed them more extensively and have proposed different usages.

Consumption losses and grazing losses should also be distinguished. Grazing losses include consumption losses as well as losses due to trampling, breakage and uprooting.

7.10 *Review*

Sections 7.10 to 7.23 briefly review some of the factors relevant to modelling the consumption and selection of food by sheep grazing arid zone pastures. These are included at this stage to form the basis for a more integrated discussion of the experimental work and the models tested.

7.11 *Methods for determining selection and preference*

Six methods have been used for determining the selection and preference for different species by grazing animals.

The impact of grazing animals on vegetation has been taken as a guide to selection by animals. Jessup (1951) observed species distributions in areas of heavy and light grazing in northwest South Australia. From these observations, and subjective estimates of the palatability of the different species, he ranked species according to what he called 'palatability'.

Other workers have observed the animals while grazing. Preferences were inferred from either the time spent grazing different species (Ivins, 1952), or from the species consumed during short time periods, compared with the species within reach (Harrington & Pratchett, 1973).

A number of grazing trial experiments have been reported in the literature. In these trials the available vegetation was estimated before and after a grazing period. Arnold (1966b) used a visual method, while others (e.g. Hamilton _et al._, 1973) have used quantitative estimates of biomass to determine losses due to grazing.

Leigh & Mulham (1966a, 1966b, 1967), Leigh _et al._ (1968) and Robards _et al._ (1967) conducted grazing trials, where although the biomass was recorded each day, they used oesophageal fistula samples collected for short grazing periods to determine preferences. The oesophageal fistula technique was pioneered in the U.S.A. and has been extensively used for determining grazing preferences (Tor~~r~~ell, 1954; Cook _et al._, 1958; Heady & Tor~~r~~ell, 1959; Van Dyne & Tor~~r~~ell, 1964).

Storr (1961) and Stewart (1967) have used plant fragments, and especially plant epidermal fragments, in dung as a method for determining dietary intake. Lange (pers. comm.) has attempted to relate plant cuticle fragments in the sheep dung to the available biomass in the Middleback area.

Kirkpatrick (1965), & Bailey _et al._ (1971) have used the mouth and stomach contents of kangaroo's shot in the field to determine the composition of their diet. Chippendale (1962, 1964, 1968) has used stomach or rumen contents to determine and compare the diets of cattle and kangaroos in Central Australia.

The last three methods described (viz, oesophageal fistulas, dung content and gut content of slaughtered animals) all have the advantage that they are a measure of actual consumption rather than grazing losses. However they all have other limitations. Slaughter allows little room for experimentation while dung analysis is difficult to interpret due to the delay between the act of selection and the appearance of the dung. The oesophageal fistula has proved successful in many situations, but results based on its use must be treated with caution. An animal with a cannula in its oesophagus must always be potentially different from other animals, even if it appears to have recovered from the operation. Also the collection periods are short and are usually carried out with fasted sheep. Appendix 3 shows some of the problems in interpreting oesophageal fistula data for sheep grazing shrublands.

7.12 *The digestive process in ruminants*

The microbial population in the rumen is essential for the breakdown of complex polysaccharides, and also supplies the animal with other essential nutrients and vitamins produced within the microbial cells. The actions of the population are carried out at a cost to the host. The microbial cells require energy for maintenance, and convert some potential energy sources to waste gases or less suitable materials. The manner of digestion also means that the passage of food through the rumen is necessarily slow.

Blaxter <u>et al</u>. (1956) proposed a model of the movement of food from the rumen and its effect on the defaecation rate and rate of food intake. They found that the movement of food in the rumen-abomasum-duodenum-faeces system could be described by a simple linear model with constant transfers and a time delay. If the sheep is assumed to eat to a constant fill of the rumen, then the consumption is controlled very much by the rate of movement of the food from the rumen. This was shown to vary with the size of the meal, its digestibility and mean particle size. It would also vary with the 'health' and nutritional status of the microbial pool (a reflection of the condition of the sheep) (McBee, 1971), and factors such as pregnancy (Graham & Williams, 1962).

The above model predicts that dry matter intake and digestibility should be positively correlated in ruminants. This has been confirmed by Playne & Haydock (1972). Whittaker (1965) showed that this model did not apply at high levels of digestibility, while Greenhalgh & Reed (1973) argued that particle size, rather than digestibility was the main determinant. Nevertheless, the model implies that ruminants have a positive feedback between digestibility (and therefore energy intake) and further consumption, which is the opposite to the non-ruminant system. This would prove to be especially important in arid pastures where many species have a high fibre content and a low digestibility. The digestibility of the diet also changes rapidy during plant growth phases and with the appearance of green ephemerals.

McClymont (1967) argued that with very highly digestible diets "phagic fatigue" stimuli operate to inhibit further grazing. He presented a verbal model of sheep feeding behaviour based on a balance of several facilitatory and inhibitory stimuli. His model brings together the highly integrated controls in common with the non-ruminant digestive systems, and the added complexity of ruminant digestion.

7.13 *The factors affecting selection*

There have been many studies of the factors affecting selection by sheep, and these have been reviewed by Arnold (1964a, b). In a series of sensory deprivation experiments Arnold (1966a, b) showed that smell, taste and touch affect selection while sight (here, the ability to see what was being grazed) did not. None of the deprivations affected animal production. Other work has supported Arnold's conclusions. Learning is also known to play a role in establishing selection preferences, and preferences for certain species are established early in life; older animals are slow to adapt to unfamiliar plants (McBride et al. 1967).

Many plant properties have been demonstrated to affect the preference shown for them by grazing animals, and no purpose would be served by listing them here. The topic has been reviewed by Ivins (1955), Arnold (1964a, b) and Heady (1964). It is clear that inherent plant properties, such as structure and specific taste compounds, can be modified in their effect on preference by external conditions such as dust, dung contamination and the animal condition. It should not be forgotten, that many plant species are well adapted to grazing and derive some benefit from it, so not all plant adaptations are towards decreasing palatability or preference (Ellison, 1960).

7.14 *Nutritional wisdom*

Nutritional wisdom may be defined as an inherent ability to select plants with particular nutritional properties needed to maintain a balanced diet. It is well known that sheep will often choose a diet that is higher in nutrients and digestibility than the available forage as a whole (e.g. Arnold, 1962; Van Dyne & Heady, 1965b; Hamilton et al. 1973). However, it is not necessarily clear whether this is nutritional wisdom as defined above, or simply a resultant of the higher digestibility and nutritive value of the most available sections of the plants. This is especially the case in shrubs, where the most available forage is the young shoot tips.

Failure to recognise this difference has led to an over-emphasis of the role of digestibility of fodders. Hamilton et al. (1973) do not appear to account for the difference in their studies, and hence emphasise the apparent active selection for higher digestibility pasture by sheep in pastures with over 500 kg ha^{-1} of green material, while commenting that the mechanism does not work at lower biomasses. Blaxter et al. (1961) recommended that the term 'palatability' be discarded and the importance of digestibility be recognised in selection shown by sheep. These are errors in emphasis rather than in fact, but they have lead to several models being proposed, which base selection entirely on digestibility (see section 7.2). The digestibility of a species may impose an upper limit on its selection by a ruminant, but it is not the only factor.

Another factor leading to the emphasis of digestion in selection, is the apparently contradictory results in experiments attempting to correlate nutritional properties with apparent palatability. Both positive, negative and a lack of relationship has been shown to occur between nutritional properties such as plant protein, sugar, fibre and mineral content and palatability (see the table from Marten [1969], reported in Westoby [1974]). Westoby argues that ruminants probably do show 'long delay learning' (Revusky & Garcia, 1970) leading to the selection of nutritious forage and the avoidance of harmful forage, although there is no direct evidence for it. Three indirect arguments indicate that it probably occurs. First, ruminants do have sensitive sensory systems on which to base learning. Second, they show non linearities in response to nutritional properties, and third, faced with variable pasture, they need such a mechanism. Westoby argues that the mechanism is not perfect; hence the variability of the experimental results. It probably leads to a sampling of different species, which agrees with the observation that ruminants "like variety" (Stoddart & Smith, 1955; and section 7.33).

7.20 *Grazing indices and grazing intake models*

The next 3 sections discuss the use of indices and models of grazing intake as reported in the literature. An index is a useful expression for describing and comparing preference differences in different grazing situations. A model of intake is a more complete description of the grazing process, describing not only species selection, but also total grazing intake.

7.21 *Grazing indices*

Many different indices have been proposed and most have been related to some set of grazing data, although one still finds new indices being proposed without any form of testing being presented (e.g. Jacobs, 1974). Most indices attempt to express species intake, usually measured as biomass or frequency in the diet, as a function of a measure of availability, although Ivins (1955) discusses some other approaches based on some of the other methods of estimating selection discussed in section 7.11.

The most commonly used index in the rangelands literature is the palatability index (RPI) as used by Van Dyne & Heady (1965a). Krueger (1972) included this index among those he compared by applying them to a common set of experimental data. These indices are given in table 7.1, and the notation given there is used throughout this chapter. Krueger pointed out the difficulties in using frequency data in comparative measurements, and concluded that either index (1) or (2) of table 7.1 was most suitable.

Another important index is that of Ivlev (1955). He used an 'electivity index' to describe selection by fishes,

E7.1 $(r - p) / (r + p)$.

He found that this was better than the RPI. Jacobs (1974) has suggested two indices, analogous to the RPI and electivity index, which better reflect the relative mortalities of the grazed or prey species;

E7.2 $r * (1 - p) / p * (1 - r)$ (c.f. RPI)

E7.3 $(r - p) / (r + p - 2 * p * r)$ (c.f. electivity)

He made no attempt to test them.

7.22 *Grazing models*

An index is not a complete description of the grazing process. It does not describe how much of each species will be eaten, nor does it give any further insight as to why such a relationship holds in the particular situation, and how transferable it may be. A complete grazing intake model is of more use for this purpose.

The literature contains a long history of predator - prey models. The first was that of Lotka (1925)and Volterra (1926). Their predator - prey equations assume that unlimited increase in food concentration will be followed by unlimited increase in food consumption. Many modifications of the Lotka - Volterra equations have been suggested, but these lie outside the mainstream of predator - prey selection studies.

Holling (1959) derived an equation based on the assumption that a consumer spends its time either searching for prey, consuming prey or in non-eating activities,

E7.4 $$C = \alpha * B / (1 + \beta * B)$$

In Holling's model consumption is asymptotic with increasing biomass because search time reduces and handling time increases to such an extent, that the predator spends most of its time eating. This is unlikely to occur in many natural situations. Satiation would usually slow the predation rate, imposing a physiological limit to consumption. Holling has dealt with this in a more complex model (Holling, 1965, 1966).

Timin (1973) has derived an equation, similar to Holling's, but including several species of predator and prey, and also intraspecific competition,

E7.5 $$C_{ij} = N_j * f_{ij} * (1 - P_j) / (1 + \Sigma[f_{ij} / g_{ij}]).$$

He considers that species j will only eat species i if it gains more energy by doing so than it would have if it has spent the time looking for more readily eaten species. This is one form of an optimization model.

Both Holling's and Timin's equations lead to asymptotic total consumption versus total available biomass curves. Ivlev (1955) proposed by analogy with physical systems a similar asymptotic curve, but with the equation,

E7.6 $$C = C^* * (1 - \exp[- \xi * B]).$$

This model, along with Holling's, and many other predator - prey models, has been the topic of a critical discussion by Royama (1971). He showed the inter-relationships between the models and demonstrated that many of the models and especially the more recent ones, are logically unsound. He warned that, "the mere fitting of curves to data can neither establish a particular mechanism nor provide verification of the model concerned."

The mainstream of the optimization approach began with MacArthur & Pianka (1966). They argued that a predator will attempt to maximize its energy intake per unit time, which is usually equivalent to maximizing its daily food intake, or minimizing the time spent hunting. They demonstrated that this strategy lead to confirmation of the observation that increased prey availability, either by poorer avoidance, better predator hunting or greater prey clumping, lead to greater prey selection specialization by the predators. Similarly, greater differences between prey species, lead to greater predator specialization.

In an accompanying paper, Emlen (1966) proposed a model which indicated that C_i / C = b_i / B, when food is limited, i.e. assuming that b_i / B represents the relative availability of species i, then it is consumed on each encounter. Only if the predator is not food limited, will c_i / C be greater or less than b_i / B. (Emlen's equations, and many of these that follow, actually refer to the numbers of prey present or consumed. Therefore frequencies of consumption and occurrence should be used rather than c_i, C, b_i and B. However these symbols have been retained for uniformity. This is equivalent to assuming that availability is represented by biomass, and that each act of predation consumes a unit biomass).

Rapport (1971) presented a modified model which showed that increased food availability lead to increased specialization. Murdoch (1969) investigated the switching of a predator from one prey to another, or from specialist to generalist feeding as the availability of the prey changed. Pulliam (1974) showed that specialization only increased if the preferred species increased in availability, i.e. specialization was unaffected by unpreferred species. He also concluded a prey type should be eaten on every occasion that it was encountered or else not at all, which means that a predator should switch only between a generalist diet (i.e. consume all prey encountered) and a perfect specialist (i.e. consume only one type of prey). However these conclusions were based on the assumption that a predator will maximize its rate of energy intake in all situations. Pulliam realised that this was unrealistic and suggested that, as a predator becomes satiated it might switch from optimizing caloric intake, to optimizing another nutrient, which would possibly lead to a new preferred prey. Also, the predator might change its view about the availability of prey throughout the course of a feeding period, and therefore a mixture of tactics might be used, while still maintaining the overall strategy of maximizing its dietry intake.

Westoby (1974) queries the applicability to large generalist herbivores, of many of the models described above. These herbivores are not usually limited by time, and can reject many encounters throughout the course of a day. They also have to choose a diet that optimizes energy intake, while fulfilling many other constraints, and Westoby suggests that a multiconstraint, linear programming model, maximizing caloric intake, is probably the most suitable model basis. However, the optimization need not be perfect since the optimization mechanisms are probably imperfect, and there is also an advantage to the animal in sampling a greater variety of vegetation, as discussed in section 7.14.

7.23 *Consumption models used in other grazing models*

A great variety of intake models has been used in other grazing models.

Van Dyne (1969a) assumed that animals transferred from one pasture type to another as the biomass of the pool being consumed, fell. Swartzman & Van Dyne (1973) distributed the maximum required intake of the animals, C*, among the pools, acording to,

E7.7 $$c_i = A_i * (\prod_{k=1}^{j-1} [1 - A_k]) * C^*$$

where A_i is the availability of taxon i. These models are proposed without any apparent, supporting evidence.

Walters & Bunnell (1971) used an equation analogous to Holling's disc equation (Holling, 1959),

E7.8 $$c_i = \alpha * p_i * b_i \; / \; (1 + \beta * \Sigma \, [p_i * b_i])$$

where p_i is a measure of preference and $\Sigma \, p_i = 1.0$. This is equivalent to an equation that is derived in section 7.42 and appendix 4. Smith & Williams (1973) used an exponential equation, similar to Ivlev (1955), for the consumption of their single pasture pool,

E7.9 $$C = \alpha * (1 - \exp[- \beta * H * B]).$$

They supported the use of height, H, in the equation, by the evidence of Allden & Whittaker (1970). Goodall (1969) also used an exponential model to estimate total consumption, but used effective biomass, E, which is a function of preference and locality, E7.10 $C = \alpha * (1.0 - \exp[\beta * E])$.

Armstrong (1971) described the 'evolution' of an intake model for sheep grazing pastures made up of several classes of green and dry pools. He assumed that the intake of any class was proportional to its digestibility. After several simpler models he proposed that, the rate of intake of green material during the day was proportional to the availability of the material and the difference between the maximum possible intake and the amount already consumed. He expressed this as

E7.11 $dc_g \,/\, db_g = k * b_g * (C^* - c_g)$

therefore,

E7.12 $Cg = \alpha * (1.0 - \exp[- \beta * b_g^{\,2}])$.

It would seem more logical to use the derivative $dc_g \,/\, dt$ rather than $dc_g \,/\, db_g$, and in a further approximation he did indeed use,

E7.13 $dc_g \,/\, dt = k\,(B - C)\,(C^* - C)$.

This approach leads to the exponential relationships common to several other models, but in this case the assumptions leading to it were also discussed.

Vickery & Hedges (1972) also based the selection of the green and dead pools in their model, on digestibility. They calculated the changes in digestibility, but appear to have chosen empirical functions for the intake model, with no further insight being sought.

7.30 *The Grazing trials*

At the start of this project (1971) there was little data about sheep selectivity in South Australian rangelands. Jessup (1951) had published subjective lists of species 'palatability' (actually, selectivity) ratings. Although his lists included most of the species found in the Middleback area, the 1 to 5 scale he used was not a suitable basis for any model. The only grazing trial conducted in the South Australian arid region was the Yudnapinna experiment (section 4.5), and very few of the results of this long trial were available. The only other published data on selectivity were the papers by Osborn and his co-workers, who often made comments on the value of various species as forage plants.

It was decided that short term, high stocking rate grazing trials, similar to those described by Leigh & Mulham (1966a), should be attempted in the Middleback area. Leigh & Mulham (1966a, b, 1967), Robards et al. (1967) and Leigh et al. (1968) described a series of trials carried out on rangelands vegetation in the Riverina district of N.S.W. They used 0.1 acre (0.04 ha) enclosures, grazed by 4 to 6 sheep, and estimated the biomass remaining within the enclosure on each day by a method similar to that of Pechanec & Pickford (1937). The observations were repeated in triplicate and calibrated against 20 quadrats outside the experimental plot.

Two trials were attempted in January of 1971 and 1972, with the aid of the undergraduate "Rangelands Ecology" class.

These trials were used to test various techniques for biomass estimation, sampling techniques and the handling of the sheep. I attempted the first complete grazing trial with the aid of one assistant in November 1972, and a second trial was carried out in conjunction with Mr. M. Andrew in May 1973. Further trials were conducted by "Rangelands Ecology" classes in 1973 and 1974.

7.31 *Biomass Measurement*

The most common form of biomass measurement in grazing trials, is the clipping and weighing of sample areas, coupled with a suitable experimental design, such as paired plots. This approach was not suitable in the trials described in this chapter. Samples had to be taken on 6 to 8 occasions throughout the trial, and it was known from experience that large sample areas had to be used in order to get estimates of the mean with reasonable variations. For example, previous work in Wertigo (section 4.1) indicated that the total sample area for a bush species like *Atriplex vesicaria* would need to be at least 100m^2 for each day. Since the total grazing area for the trial was only 1000m^2, destructive sample techniques were regarded as being unsuitable.

There does not exist a reliable, non-destructive method for measuring the biomass of bushy perennials. The most successful 'machine approach' to date, has been the capacitance meter (or probe) (Fletcher & Robinson, 1956; Alcock, 1964). Its main application has been in pasture but it has been applied with some success to shrubs. Carpenter et al. (1973)

found that the meter readings correlated best with the oven dry weights of the 'soft' material, i.e. shrub leaves and new shrub stems, grasses and forbs. Andrew (pers. comm., 1974) in some preliminary trials has found that a capacitance meter can be used to estimate the leaf material of *Kochia sedifolia* at Middleback. However, at the start of the project a capacitance meter was not available, and did not seem to be a particularly promising approach for shrubs. Also, a method that could distinguish between different species when they are growing entangled with each other was needed.

The other, most successful method of non-destructive biomass estimation, is visual assessment. These methods include the visual obstruction techniques (e.g. Robel et al., 1970; Springfield, 1974), where the plant is projected on to a background scale, and correlations are established between the amount of the background obscured and the biomass. The other common visual approach is based on 'subjective' estimates of biomass (hereafter called visual estimates). Morley et al. (1964) and Hutchings & Schmautz, (1969) used visual estimates of the total biomass of sample plots and devised methods to minimize errors due to individual differences, fatigue and experience. Fatchen (unpublished Honours thesis, 1971) used colour 'polaroid' photographs as an aid in visually estimating the biomass of grass plots in the South Australian area.

Pechanec & Pickford (1937) published a visual estimation technique based on the use of standard, known weight samples of the species being estimated. They recommended that samples of basic size units such as 10g, 50g, 100g etc, be defined and that the operator train with these for up to several days before estimating the experimental plots. They recommended training on one species at a time. Many variations of this technique have been used, and the methods used in the grazing trials described in this chapter are based on it. Some workers have used techniques similar to Pechanec & Pickford to estimate variables other than biomass, e.g. Williams (1954) developed a visual estimation technique for leaf areas in plant physiological studies. Laycock et al. (1972) compared three methods for determining the diet, utilization and trampling damage on sheep ranges in the U.S.A. They found that visual estimation of percentage utilization by weight gave results similar to the utilization estimated by the oesophageal fistula, while the paired plot method tended to over-estimate the utilization since it included the trampling losses. Visual estimation was the most efficient approach.

The Pechanec & Pickford method was chosen for use in the grazing trials since it was non-destructive, it distinguished between any taxa the operator wished to define, it was applicable to almost all the taxa important at Middleback, and other workers had indicated that it was sufficiently accurate. Its disadvantages were, the long training times required for each species, its subjectiveness (especially, in a grazing trial where biomasses are expected to decline), and its dependence on the mental state of the operator, which is a critical short-coming in hot conditions.

The final techniques for the various species are described below. These techniques were the results of many different approaches, and were themselves modified if needed.

A. vesicaria was chosen as the bush taxon for which the technique was developed, because it is the most important of the bushes and it appeared to be the simplest to estimate. From the results of the early grazing trials it was decided to estimate the edible biomass of the bushes. This was determined by examining the biomass remaining on bushes heavily grazed by sheep. A method of stripping the bushes by hand which resulted in an apparently similar removal of leaves and new twig, was developed. This process was time consuming, taking about 1 minute for small bushes, to 10 minutes or more for the largest. However, it was directly related to what the sheep ate, and also to the visual impression of the bulk of the bush, and it excluded the variable contribution to biomass due to woody material. A sample of the species being estimated was collected nearby and the biomass of several complete bushes was estimated in terms of multiples of this sample. (This is similar to the 'micro-unit of forage' used by Shoop & McIlvain (1963)). The bushes and the sample were then stripped and weighed individually to determine the wet weight, and this process was repeated several times as initial training. Usually some criterion, such as, "three estimates of bush biomass with a mean error of less than 10% and no individual error greater than 15%" was used to determine when sufficient training had been completed.

It was found that one of the most common sources of error was due to a wrong visual impression of the size of the sample. This would lead to consistently high or low estimates. In order to overcome this, instead of stripping and weighing the sample, 5 or more subsamples of equal size were collected during the course of the estimation of the bushes. These subsamples were then stripped and weighed, and the mean weight was used as the sample weight. This method also had the advantage, that during long periods of estimating, the collection of subsamples compensated for any drift due to fatigue that might have occurred. The subsamples also, better encompassed the range of variation of the bush being estimated, and therefore compensated for errors due to different impressions of biomass for sparse leaved bushes, large leaved bushes and so on. An even better approach would have been to establish a calibration curve by estimating and stripping whole bushes, but this would be very time consuming and it was considered that the time was better spent on more training. Figure 7.1 summarizes some of the results obtained for *A. vesicaria*, using this method. This technique, or a slight modification of it was applied to all the bush species.

The grass species were estimated with the aid of a range of samples. These samples were chosen to encompass the full range of size, growth habit, and degree of utilization encountered in the target population. They were trimmed to match the maximum degree that sheep could utilize the species, weighed and taped to a board. The grass biomass was estimated by visually assessing the exact weight (i.e. with extrapolation between sample sizes) for each tussock or bunch. A training period similar to that described above was used except that small plots were estimated rather than individual tussocks. There was a problem in defining the maximum degree of utilization, since sheep had a tendancy to pull up tussocks by the roots. Some of these were dropped only partially eaten, but it was possible that some were eaten completely.

The bassias posed a special problem since they have neither a complete bush habit, nor are they sufficiently similar to a grass to use that technique. Their thorniness also prevents effective stripping. It was found that sheep could bite off bassias near the ground and eat the entire above ground portion of the plant. An 'hybrid' technique, using a range of samples for the smaller bushes, and a micro-unit for the larger ones was adopted. Again, training was carried out by estimating small plots.

Various modifications of the above techniques were used for other minor species. The only major difference was *Chenopodium ulicinum*. This is a low spreading bush with brittle stems and very small leaves. Various volumetric techniques were attempted and proved sufficient to estimate the biomass to ± 20%. However the species contributed very little to the total biomass and was rarely grazed.

For all species it was possible to train to be able to estimate biomass to less than 20% error, and in some species, less than 10%. It was recognised that these errors might increase during the period of estimating the experimental plots, although checks at the end of the estimating period showed no larger errors than those at the end of the training. In each experimental trial a large number of bushes (50 to 150) and at least 25 to 36 quadrats for other species, were estimated independently. This would further reduce the error associated with the mean. (This reduction would be proportional to $1/\sqrt{n}$, where n is the number of independent estimates, if the errors could be assumed to be randomly and normally distributed.)

7.32 *Experimental details*

All the trials followed the same basic design. An experimental area was selected and a 0.1 ha rectangular area fenced, with a water yard and a hold-yard adjacent (fig. 7.2). The sheep were placed in the holding yard so that they would become accustomed to the vegetation (although this was probably not necessary since they came from the same paddock as the experimental area or an adjacent one), and to the presence of people. Southcott et al. (1962) found that a flock size of 4 or more was apparently suitable for trials such as these, and it was calculated that 6 sheep would graze the area at a suitable rate for the experiment. Two to three year old merino ewes were used in each experiment excepting that of May 1973 where wethers were used instead of ewes.

Within the experimental area a grid of quadrats, as shown in figure 7.2 was laid out. The quadrats varied in size, from 2m x 4m for some of the bushes to 0.2m x 0.5m for small species and litter. The next 3 to 4 days were spent training to estimate the biomasses and in making the initial biomass estimates (day 0).

The sheep were allowed into the experimental area on the morning of day 0. They had free access to water and shade but not to the holding yard. They were not disturbed until the next day. The biomass estimations were done between 11-00 am to 3-00 pm daily since it had been observed that sheep were usually not grazing at this time. The sheep were shut in the water yard during the period people were present. This process was repeated until the conclusion of the experiment; usually 6 to 7 days.

Training periods were carried out at a nearby site, before disturbing the sheep, and the time the sheep were held in the water yard was usually less than 2 hours. Rainy weather during the experiment would have caused serious disruption, or even halted it, since it was not possible to train sufficiently with wet plants. Fortunately no rain was recorded during any of the experiments.

7.33 *Results*

The results of 3 trials, November 1972, May 1973 and a student trial of January 1973 are summarized in table 7.2. A second student trial was conducted in January 1973, but is not included in the detailed analysis because of errors in estimating the biomass of some species. The errors associated with the biomass estimates make the interpretation of the results difficult, especially when consumptions, calculated as the difference between two biomass estimates, are used.

A qualitative review of the results produces some useful information. The sheep acted as generalist feeders taking some of all the available species every day. The results include losses due to trampling and breakage as part of the grazing losses, so the actual consumption of the species was less than shown in the tables. However, observation of the sheep while grazing, confirmed that they did vary their diet, often moving from one species to another every few minutes or even more rapidly. This observation indicated that an optimization model like that of Pulliam (1974) would not be an adequate description of the sheep consumptive behaviour, since it seems unlikely that the sheep would be reassessing its tactics quite so rapidly.

The results give an indication of the ranking of the selectabilities of the taxa included in the trials. Grasses, excepting for the mature plants of species with large, 'spikey' flowers (e.g. *Stipa nitida* and *Danthonia caespitosa*), were the most preferred taxa. Other small, soft taxa, such as young bassias, and *Kochia* species were also highly preferred. *A. vesicaria* was the most preferred of the species making a major contribution to the available biomass, although mature bassias (*B. patenticuspis* and *B. obliquicuspis*) were also highly preferred. *K. sedifolia* was only selected when little else was available.

The change in total grazing losses as the biomass fell, was very similar in all the experiments. Initially the sheep removed about 1.0 to 2.0 kg of biomass per head, but this fell rapidly once the total available in the enclosure fell below about 10 kg (fig. 7.3).

7.40 *The sheep consumption model*

A consumption model needs to account for two processes; the decline in consumption as available biomass falls, and the contribution of each of the available species to the total consumption as the biomass falls. I proposed several different models, and tested them against the grazing trial data. Some of these models were also investigated by Andrew (unpublished honours thesis, 1973) and will not be dealt with in detail here.

The decline in consumption, can arise in any of 3 ways, or from a combination of them. The animals could be limited by the time available for grazing, so that as the prey (forage) availability fell, less could be found and eaten (c.f. the Holling models). This seems unlikely to be the limitation in these grazing trials. If it is assumed that sheep graze for 8 hours per day and move a 1 km hr^{-1} while doing so, and search a strip 0.5m wide, then they would scan an area of about 0.4 ha day^{-1}. Even in times of low biomass (e.g. 100 kg ha^{-1}), this area would contain about 20 to 30 times the daily biomass requirement. They would also be able to thoroughly search the total grazing trial area (0.1 ha) each day. These figures are arbitrary, but I believe them to be conservative, in that a hungry sheep would adopt a much larger search range than assumed here.

The above approach assumes that the sheep can potentially eat all of the biomass they find. If it is assumed that the sheep reject much of the biomass they encounter (which they obviously must do), and do not change the rejection rate sufficiently as the available biomass falls, then their consumption may fall. This is the basis of the models discussed later. A third reason for the fall in consumption may be that the digestibility of the available forage falls as the available biomass falls. This means that the rate of passage through the rumen is less, and hence intake must fall (c.f. Blaxter et al., 1961). It was not possible to test whether this occurred during the trials since no estimates of the digestibility of the available forage were made. If the digestion rate was limiting the ingestion rate, then this would show up as a reduction in the amount of time spent grazing each day. It was not known how the grazing time changed throughout the trials. 'Grazing clocks' (Allden, 1962) were used in the trials carried out by the students in January 1974. These clocks operated by allowing a pendulum to scratch a line on a rotating, 24 hour dial, whenever the sheep put its head down to eat. However, since many of the bushes were as high as the sheep, and since the sheep often sheltered from the sun by putting their heads down in the shade of the other sheep, it is doubtful whether the 'grazing time' records were particularly accurate.

7.41 *The selection model*

A simple model of forage selection among the different species available, was derived by assuming that the consumption of a species is proportional to the number of times it is encountered by the sheep, and to a preference factor which expresses the probability of the sheep consuming any of the species on encountering it. The intake is also assumed to be proportional to the average amount actually consumed on a 'successful' encounter. This model may be stated as follows. Assume a sheep makes n searches for food each day. A search is defined as the activity between one encounter with some forage and the next. The value of n will change with many factors, including the amount of forage available, and the ingestion rate as influenced by the digestion rate. Assume that the probability of the species encountered being species i is b_i / B, and that the probability of any of the species being consumed is π_i, and the mean amount consumed at a successful encounter is w_i (let $p_i = \pi_i * w_i$). Therefore,

E7.14 $$c_i = n * p_i * b_i / B$$

and for m species,

E7.15 $$C = \sum_{i=1}^{m} c_i = n * \sum_{i=1}^{m} (p_i * b_i) / B$$

and (abbreviating the $\sum_{i=1}^{m}$ notation, to Σ),

E7.16 $$c_i / C = (p_i * b_i) / \Sigma (p_i * b_i).$$

The values of p_i could be estimated from the experimental data by plotting c_i / C against b_i and estimating $p_i / \Sigma (p_i * b_i)$ from the slope of the line by least squares analysis, or some other appropriate method. This method proved to be unsatisfactory due to the large errors associated with c_i. Therefore the value c_i was replaced by the approximation $c_i = - db_i / dt$, which expresses consumption as the rate of decline of the available biomass and therefore,

E7.17 $$-db_i / dt = ([p_i * b_i] / \Sigma [p_i * b_i]) * C.$$

The values of p_i could be estimated by solving the set of simultaneous, non-linear, differential equations using an appropriate computer program. However the inaccuracies in the data meant that any automatic method might have lead to poor solutions, so they were solved manually after making the approximation that $\Sigma (p_i * b_i) = \propto * B$, and therefore,

E7.18 $$-db_i/b_i = (p_i * C / [\propto * B]) dt$$

and, on integrating,

E7.19 $$\ln(b_i) = \ln(b_i^*) - p_i * (C * t) / (\propto * B)$$

where b_i^* is the initial biomass of species i. The values of $p_i /\propto$ were estimated by plotting $\ln (b_i)$ against $C * t/B$ and estimating the slope after eliminating points showing a large variation from the linear relationship. The estimates of the slope were then used to calculate a new estimate of $\Sigma (p_i * b_i)$, and the process repeated. Only the proportional relationships between the p_i values are obtained by this method, but this is all that is necessary.

The steps in the iterative procedure are shown for the November 1972 data in figure 7.4, and the final iteration for the other trials in figures 7.5 & 7.6. The estimates of p_i are summarized in table 7.3. The values have been expressed relative to p_i for *A. vesicaria* equal to 1.0, or the taxon *B. obliquicuspis/B. patenticuspis* equal to 1.0. The results in the different trials are not strictly comparable since the p_i value of the base line species may itself have changed from trial to trial. *A. vesicaria* is the most suitable baseline since it is usually a major component of the available biomass and as a perennial bush it is less susceptable to seasonal variations in selectibility.

The taxon *Bassia patenticuspis/B. obliquicuspis* showed a range of p_i values, indicating that in two trials sheep preferred them to *A. vesicaria*, but not so in the other trial. *B. obliquicuspis* and *B. patenticuspis* are morphologically very similar, mainly differing in the angle between the spines on the fruit, although they can usually be distinguished in the field by slight habit and colour differences. They were estimated separately in the trials but have been grouped in the analysis of these data since they are difficult to distinguish once they have been grazed, and because in each trial either one of the species was available in a much greater biomass than the other. Slight differences in the preference were shown for these species, but these were more likely correlated with slight size and maturity differences between the two populations rather than with inherent species differences. In the November 1972 trial the bassias were mature and in fruit, but were still fleshy and soft. The January 1973 trial was held only a few metres from the November trial, and the p_i value was approximately the same. Good rains fell in February and March of 1973, but in the May 1973 trial the *B. obliquicuspis* and *B. patenticuspis* biomass consisted mainly of mature plants of the same approximate age group as those plants encountered in the earlier trials. The plants in the May trial were more woody and had dry fruits, and, not unexpectedly, a p_i value much less than in the earlier trials.

The p_i values for the other *Bassia* species varied widely. *B. sclerolaenoides*, a small woolly, but thornless, species was not favoured by the sheep. *B. biflora* and *B. uniflora* showed the highest p_i value of all the trials. These species were abundant, and were soft and thornless in the January trial.

The grasses were usually highly preferred, with the exception of *Stipa nitida* and *Danthonia caespitosa* in the January 1973 trial. In this trial most of the individual plants had dry flowering heads containing sharp pointed awns and seeds.

Kochia sedifolia was the least preferred of the major species, although the sheep ate large quantities of it as the other species were grazed out. Observation of a few bushes of *K. pyramidata* in the trials indicated that it was about as preferred as the *K. sedifolia*.

Chenopodium ulicinum is a common species in the Middleback area, and was available in the trials. It is a low compact bush, with dense, tangled, thin, woody twigs and small leaves. No successful method of non-destructive sampling was ever devised, but observations showed that the sheep did not consume any significant amount of it, even on the last days of the trials.

In the November 1972 and January 1973 trials some *Casuarina cristata* branches were within the reach of the sheep. These were not estimated since it was difficult to judge how much was within the sheep's reach, and the total biomass was insignificant. They were highly preferred by sheep, and on some occasions individual sheep were observed standing on their hind legs or attempting to climb the tree in order to reach leaves. Most of the tree species of the area are eaten by sheep, as it is attested by their uniform pruning to sheep height and the lack of young trees and seedlings.

Several variations of the model discussed above were proposed and tested. These included the situation where, in each search, a sheep was assumed to find 2 species from which it chose the most preferred, and the extension of this model to where the number of species encountered as a result of a search was described by Poisson distribution. These were tested and discussed in more detail by Andrew (1973) as an Honours project. They do not give a better fit than the simple model described above, and therefore there is no justification for using them in the grazing model. It was decided to use the equation,

$$E7.20 \qquad c_i = p_i * b_i * C \, / \, \Sigma \, (p_i * b_i),$$

to estimate the distribution of the consumption between the species in the grazing model. The values of p_i used for the taxa included in the model are given in table 7.3. These values would change with the season, but there was insufficient data available to include this in the present version of the model.

7.42 *The intake model*

Equation 7.16 requires an independent estimate of C, the total consumption during the time period for which the equation is being evaluated. The model used above can be extended to give an estimate of C, based on a model of the form proposed by Holling (1959), i.e.

$$E7.21 \qquad C = k * T \, / \, (\tau + g)$$

where, T is the total time spent grazing, τ is the mean search time, g the mean time to graze the forage found, and k is a constant. If it is assumed that the mean time between encountering a unit of potential consumption is proportional to 1/B (this is equivalent to assuming random search with respect to the vegetation) then it can be shown (appendix 4) that,

$$E7.22 \qquad C = \alpha * T * \Sigma \, (p_i * b_i) \, / \, (1 + \beta * \Sigma \, [p_i * b_i]),$$

where 'α' and 'β' are constants. This is analogous to the equation derived by Holling. However it cannot be assumed that T is constant. As $\Sigma\ (p_i * b_i)$ fell, then ingestion may be limited by digestion, and T would fall.

The situation is further complicated by the fact that only the proportional relationships between the p_i values within an experiment were calculated. This means that the data could not be used to calculate $\Sigma\ (p_i * b_i)$ values and then, the results of the several grazing trials pooled to estimate the constants α and β. Even if this was possible, it would give an estimate of the total daily consumption rather than the consumption within the hourly time step required in the grazing model.

Therefore, it was decided not to calculate C by equation 7.22. Instead the maximum total daily consumption was estimated by fitting both a Holling type function (i.e. equation 7.21) and the other commonly used equation for data of this form,

E7.23 $$C = \alpha * (1.0 - \exp [- \beta * B]).$$

Equation 7.21 was fitted by plotting 1/C against 1/B and determining the values of α and β by simple linear regression. This approach is most sensitive to low values of B, since small errors in B result in large errors in 1/B. Estimates of B of less than 80 kg ha^{-1} were omitted from the analysis since these had a large relative error. For similar reasons, the highest C value (2.25 kg sheep^{-1} day^{-1} in the May 1973 trial) was omitted from the analysis for equation 7.23, since, when the equation was linearized by transforming it to, E7.24 $\ln([\alpha - C] / \alpha) = - \beta * B,$

any fitting technique is very sensitive to values of $C \approx \alpha$.

Neither equation is a particularly good description of the data. The best fit equations were,

E7.25 $C = 0.0086 * B / (1 + 0.0046 * B)$ ... kg sheep^{-1} day^{-1}

and,

E7.26 $C = 2.3 * (1.0 - \exp[- 0.00235 * B])$ ... kg sheep^{-1} day^{-1}

which have asymptotes of 1.87 and 2.3 kg sheep^{-1} day^{-1} respectively (fig. 7.3). These represent the total grazing losses per day and not the sheep ingestion. The ingestion may be estimated by correcting the grazing losses for litter fall during the experiment. Only in the May 1973 experiments were adequate estimates of litter fall made, and, even in this trial, the area of the quadrats (72 quadrats 0.5m x 0.1m) was still too small. The litter losses over the first 5 days of the trial indicate that only 63% of the grazing losses were due to ingestion. The litter fall on the last two days were not included since these were affected by the heavy grazing of *K. sedifolia*. The sheep were particularly destructive in breaking off whole branches while trying to reach more succulent foliage. The total quadrat area was insufficient to account for the variance caused by these large units of litter. It is interesting to note that the litter fall increases as the experiment continued which implies that the estimates of grazing losses have a larger breakage and trampling component at low values of B. This may account for the underestimation of C by both equations at low values of B. The ingestion losses as estimated after correction for the litter fall asymptote at 1.2 and 1.4 kg sheep^{-1} day^{-1} respectively. These are within the range of dry matter intakes reported for sheep on low quality diets.

The above analyses give a basis for a sheep intake model. The hourly ingestion of forage is yet to be described, but the relationship between the total daily ingestion, and the mean biomass per unit area in the area searched by the sheep may be estimated from either equation 7.25 or 7.26. The simple model described in equation 7.16, appears to be sufficient to describe the distribution of the ingestion among the species.

This model was tested by applying it to the November 1972 data. The initial biomasses of each of the species and the estimated values of p_i were used, along with equations 7.25 and 7.16 to calculate the fall in biomass of the major species (fig. 7.7). This is only a verification and not a proper validation of the model, but it does give an estimate as to how sensitive the model is to the approximations made in its derivation. The variation between the experimental data and the simulated result is due to residual variance remaining after fitting the linear regressions to estimate

p_i, and the variance due to the scatter of the data about the exponential function used to estimate the daily food intake.

7.43 *The hunger model*

This section describes in detail the intake model and its interaction with the hunger trigger described in sections 8.400 and 8.420. The hourly time step in the modelling of sheep grazing behaviour makes possible a model of the digestive process. Blaxter et al. (1956) described a model of the flow of food through the alimentary tract of a sheep. They dealt with the 3 main sections of the tract as shown below and where k_1 and k_2 are simple rate constants.

$$\text{rumen} \xrightarrow{k_1} \text{abomasum} \xrightarrow{k_2} \text{duodenum} \xrightarrow{\substack{\text{time}\\\text{delay}}} \text{faeces}$$

This model described their experimental results very well, and it has been used as the basis of the model of the consumption process in the grazing model.

Only the first section of the flow through the alimentary tract is included in the consumption model, i.e. flow from the rumen to the abomasum. This simplification is made because, although eating behaviour is controlled by the hypothalamus in response to stimuli from many parts of the body, the rumen fill is a major determinant. According to Blaxter's model the rumen fill is dependent only on the first rate constant. Therefore the rumen contents are modelled by being incremented by food intake and decreased by an outflow proportional to the rumen fill. Phillipson (1952) showed that the movement of food through the alimentary tract to the duodenum occurs throughout the day. The rate constant for the flow from the rumen is dependent on many variables, including food particle size, the food type and the state of the ruminal flora. In this model it has been set at 0.1, which gives a realistic daily intake. This is the approximate value determined by Blaxter et al. (1956) for a medium ground, grass diet. There is not sufficient data to vary this constant in the model as the diet changes.

The sheep are assumed to eat a constant rumen fill in the model. A value of 0.75 kg is used in the model, which is about 60% of total gut food content as estimated by Blaxter et al. In experiments described by Larredo & Minson (1973) the average dry weight of the rumen contents of sheep fed grass diets, was 0.70 kg. Once the rumen is filled the sheep do not eat until 1/3 of the rumen contents have been lost as outflow.

This is the basis of the hunger trigger as used in the sheep movement model. The model actually sets two hunger triggers; one when the rumenis less than 2/3 full, and one when it is more than 2/3 full. This allows the sheep behaviour in relation to conflicting demands such as to shelter, or to graze, to be modelled in more detail by simple changes to the decision table described in section 8.400.

The amount of consumption during any one hour is dependent on the pasture available and on the satiation of the sheep. No appropriate experimental studies have been made on the rate of sheep grazing so this section of the model is arbitrary. The sheep are assumed to eat at a rate of up to a maximum of 0.4

kg hr^{-1} of dry weight plant material. This rate is reduced by a function accounting for the availability of the forage. The equation 7.25 derived in section 7.42 showing the decline in daily intake as the available biomass falls is taken as a basis for this factor although no causality is implied. The equation is adjusted to take values between 0. and 1.0. The maximum hourly intake is therefore,

$$\text{E7.27} \qquad M = 0.4 * (0.0046 * B / [1 + 0.0046 * B]).$$

This is further reduced by a satiation factor, which reduces the rate of intake to 1/4 as the rumen fills,

$$\text{E7.28} \qquad \text{intake rate} = M * (1 - \text{rumen fill}). \qquad \ldots \text{ kg hr}^{-1}$$

The species composition of this intake is determined by equation 7.16.

This model will not give results exactly the same as those of the grazing trials. The relationship between total daily consumption C and the mean available biomass throughout the day's grazing, B, will not be the same as predicted by equation 7.25, since the model predicts that the sheep will increase their grazing time at the expense of resting time in order to maintain their consumption more than did the sheep in the trials. This could be corrected by modifying equation 7.27. However it would be unrealistic to expect the behaviour of sheep in a small enclosure and those in a large paddock to be identical. The model gives grazing times and intakes which appear to be reasonable when compared with published results and leads to a realistic daily behaviour pattern (see section 8.5). The processes and parameters included in the model all seem to be realistic when compared with published results or experimental work reported in this thesis.

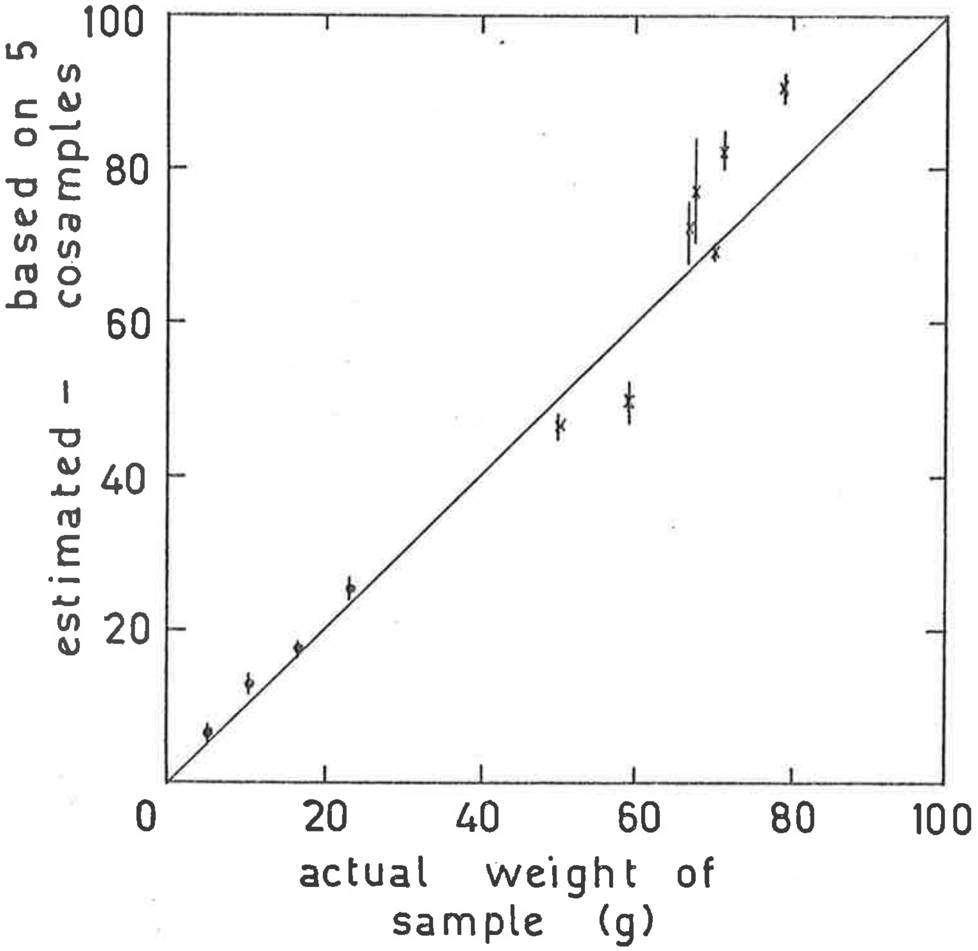


Fig. 7.1a. A graph showing the relationship between the actual weight of the samples used in a grazing trial, and its estimated weight based on 5 co-samples. The lines show the 95% confidence limits of the mean. The graph shows that the estimator's 'image' of the biomass of the sample is often consistently high or low. The mean weight of the co-samples was used in estimating the biomasses in the experiment. *K. sedifolia* samples are shown by -x-, and *A. vesicaria* by -●-.

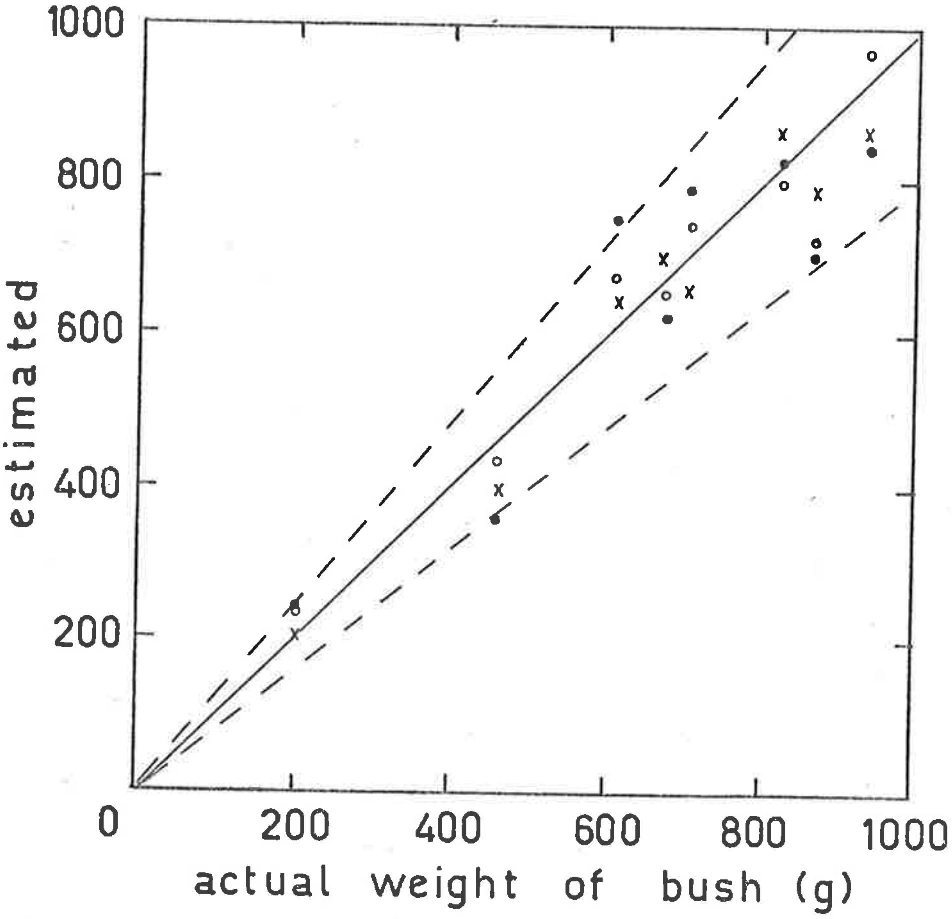


Fig. 7.1b. The biomasses of 8 *K. sedifolia* bushes estimated on 3 separate occasions with different samples. The dashed lines represent ± 20% error.

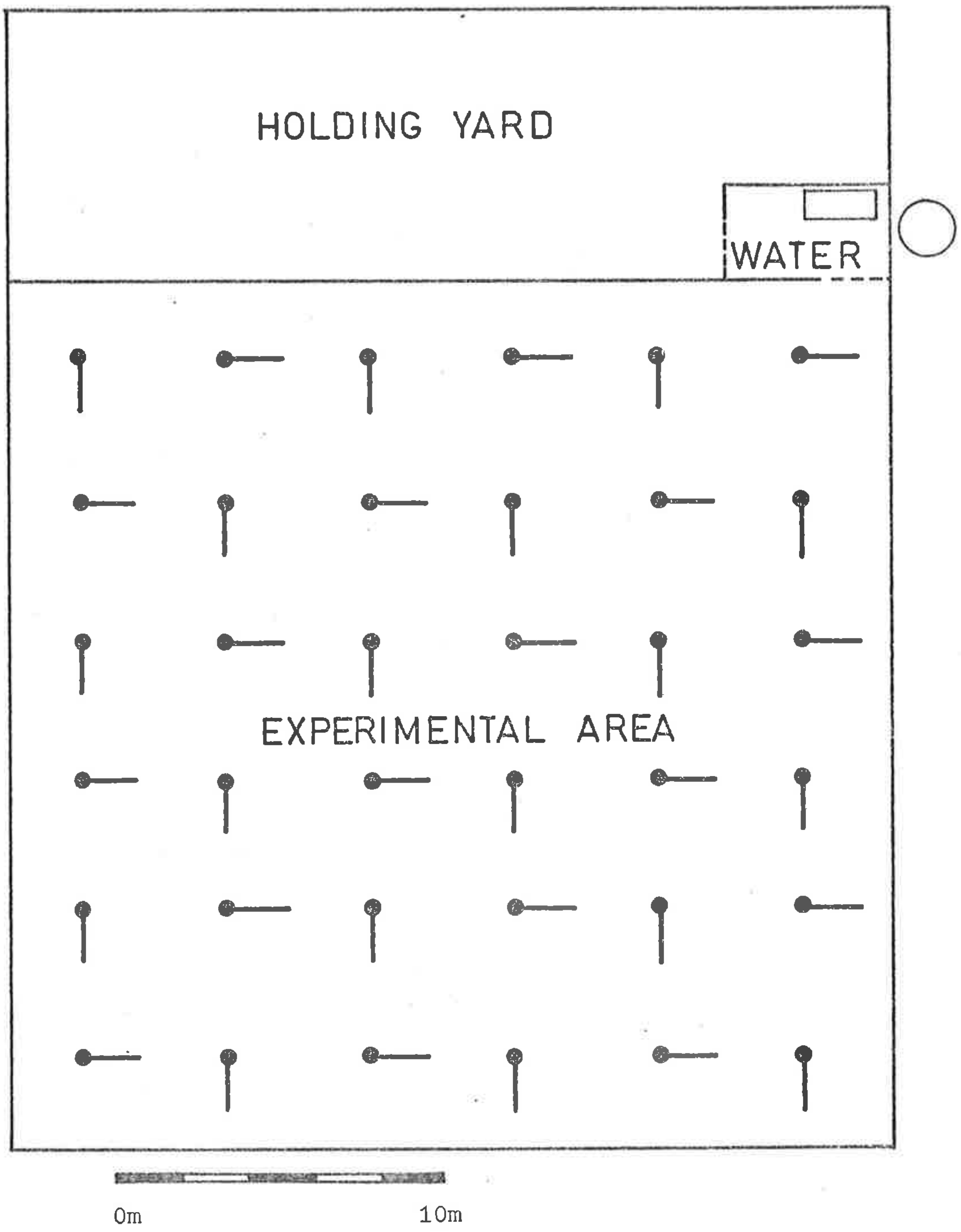


Fig. 7.2. The layout of the fencing and quadrats in the grazing experiments. The quadrats were marked only by small, wire loops and were laid on a regular grid so that they would be easier to find.

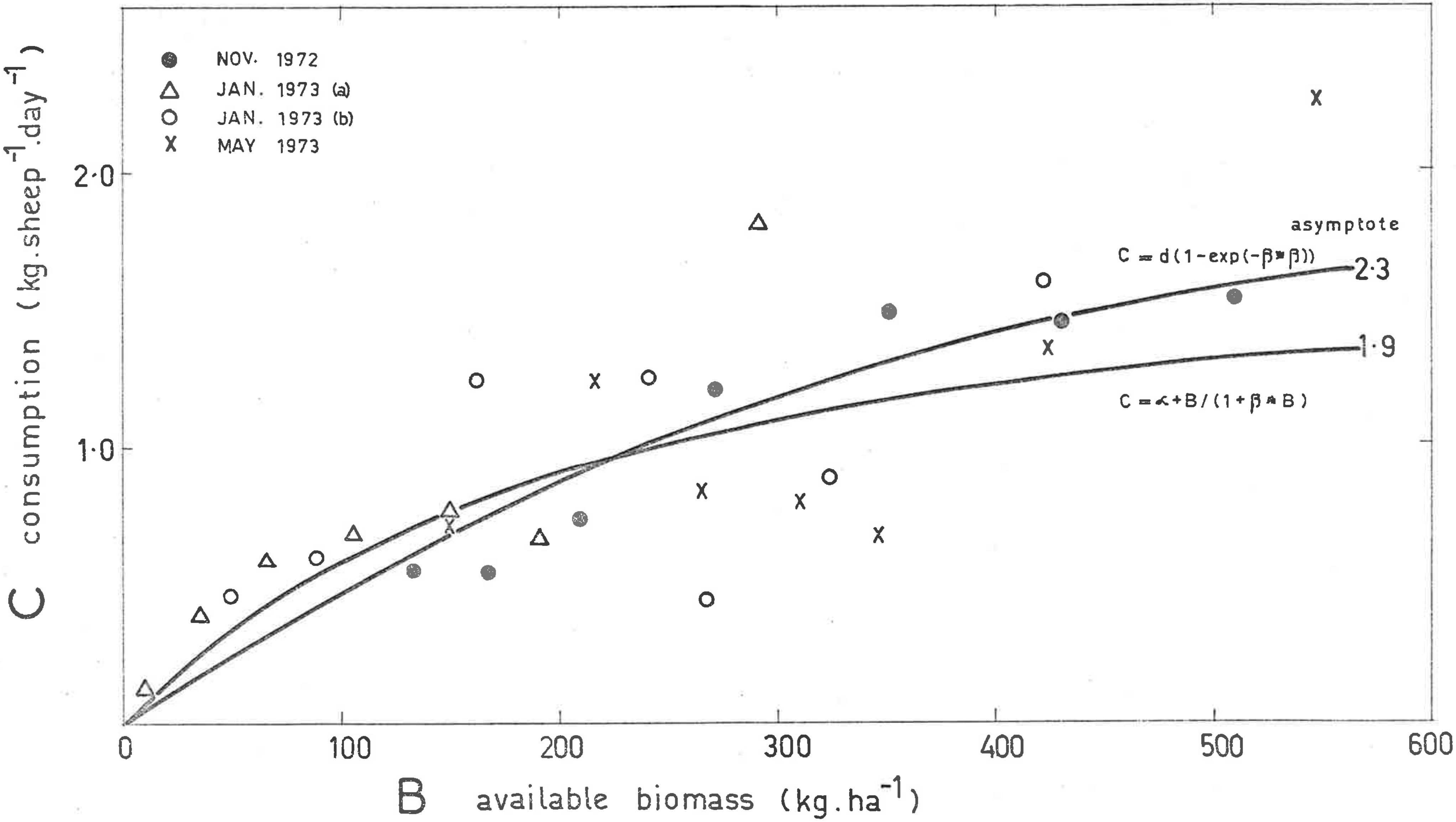


Fig. 7.3. The daily consumption (dry weight) versus the estimated, available, edible biomass (dry weight) for four experiments.

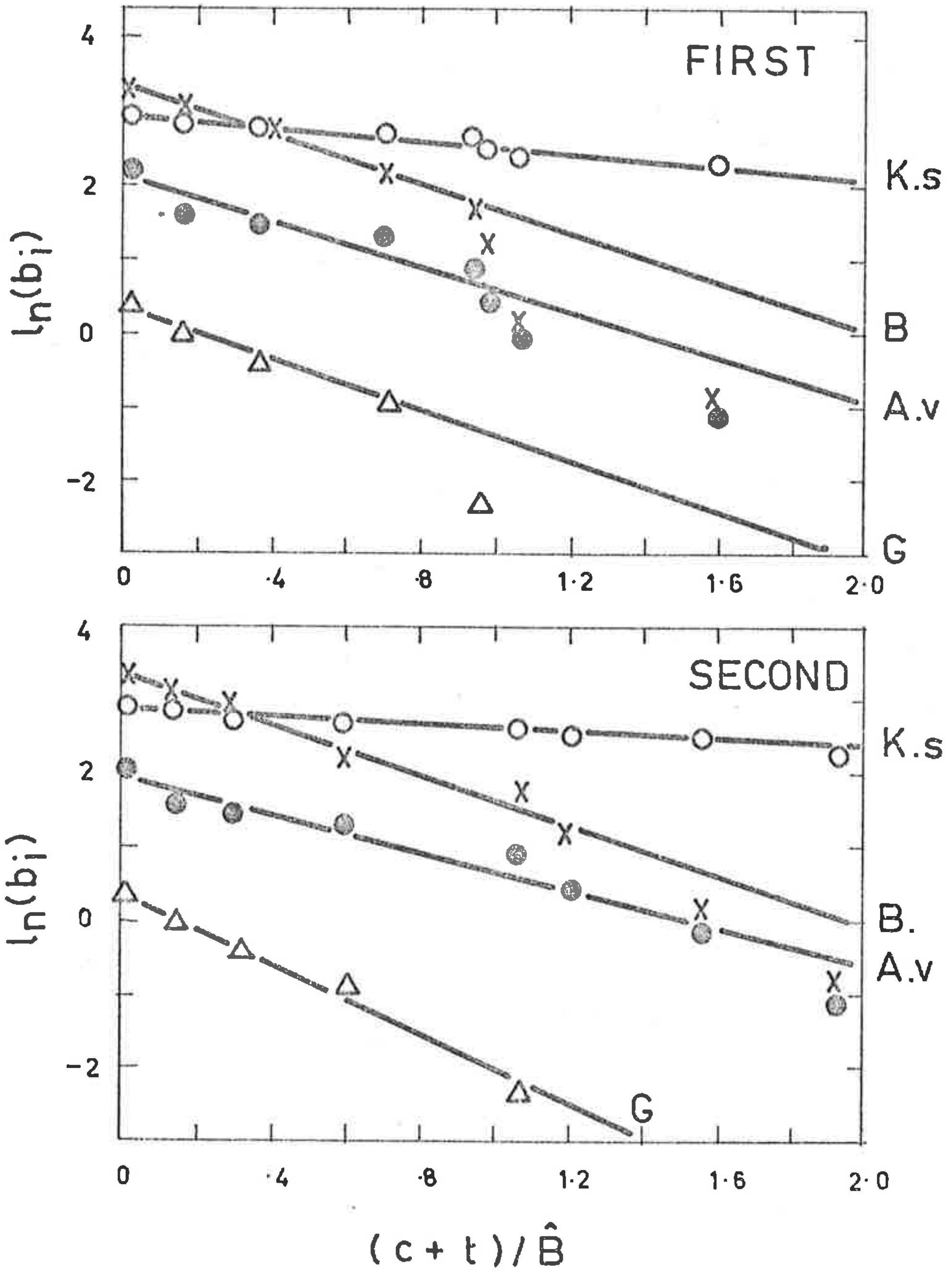


Fig. 7.4a. The first and second iteration in estimating the p_i values for the November 1972 grazing trial.

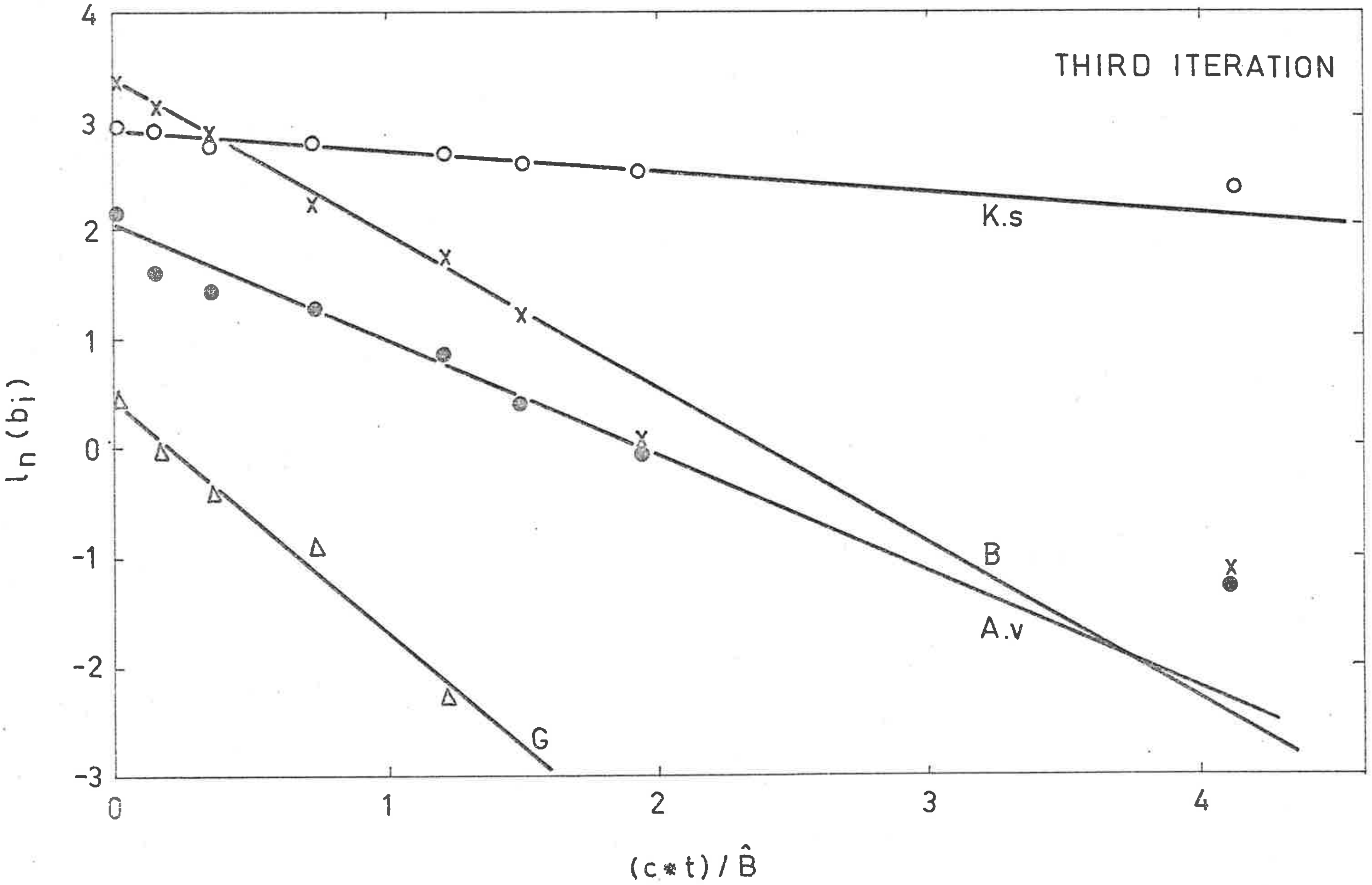


Fig. 7.4b. The final iteration in estimating the p_i values in the November 1972 grazing trial.

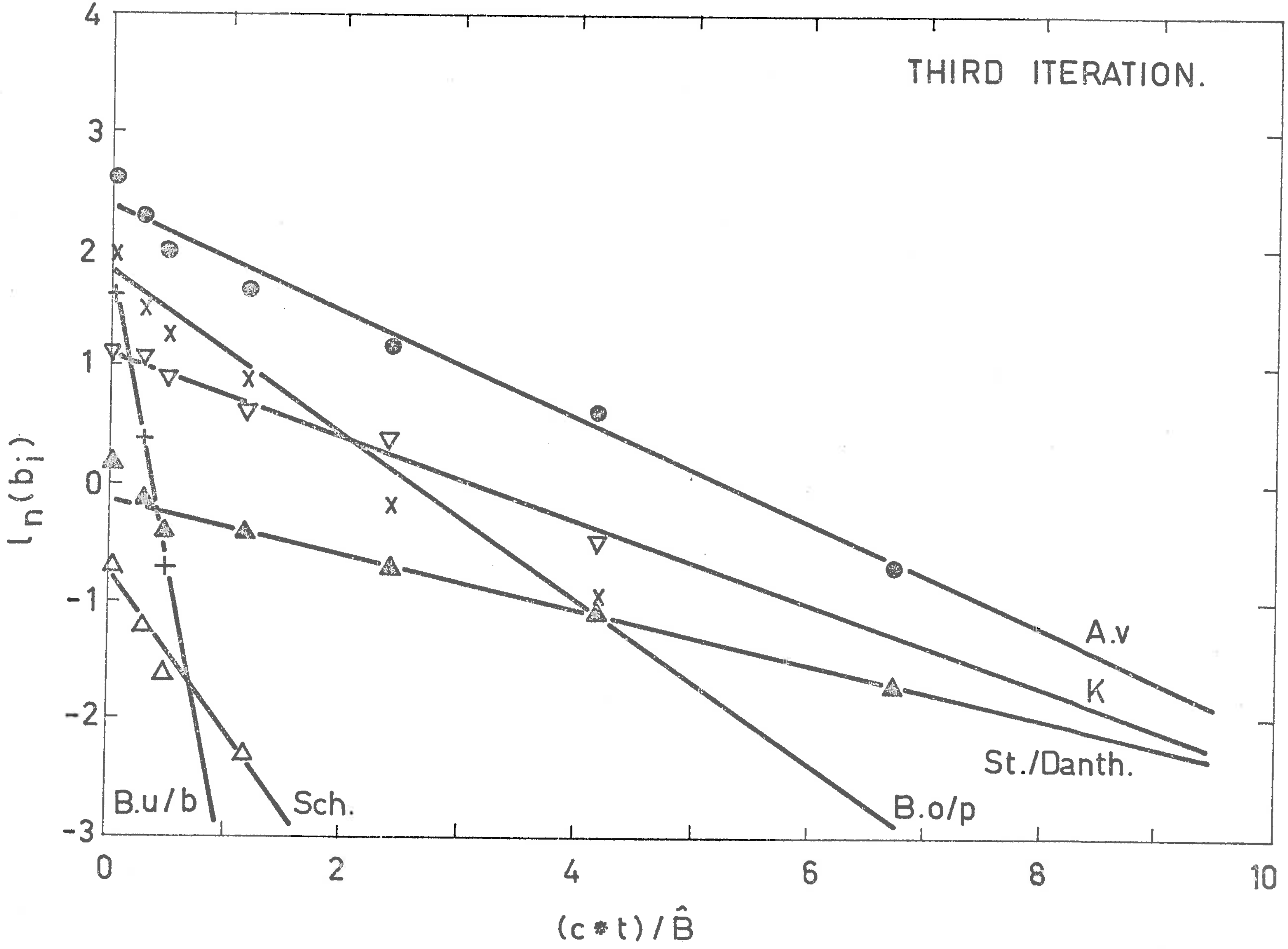


Fig. 7.5. The final iteration for the January 1972 trial.

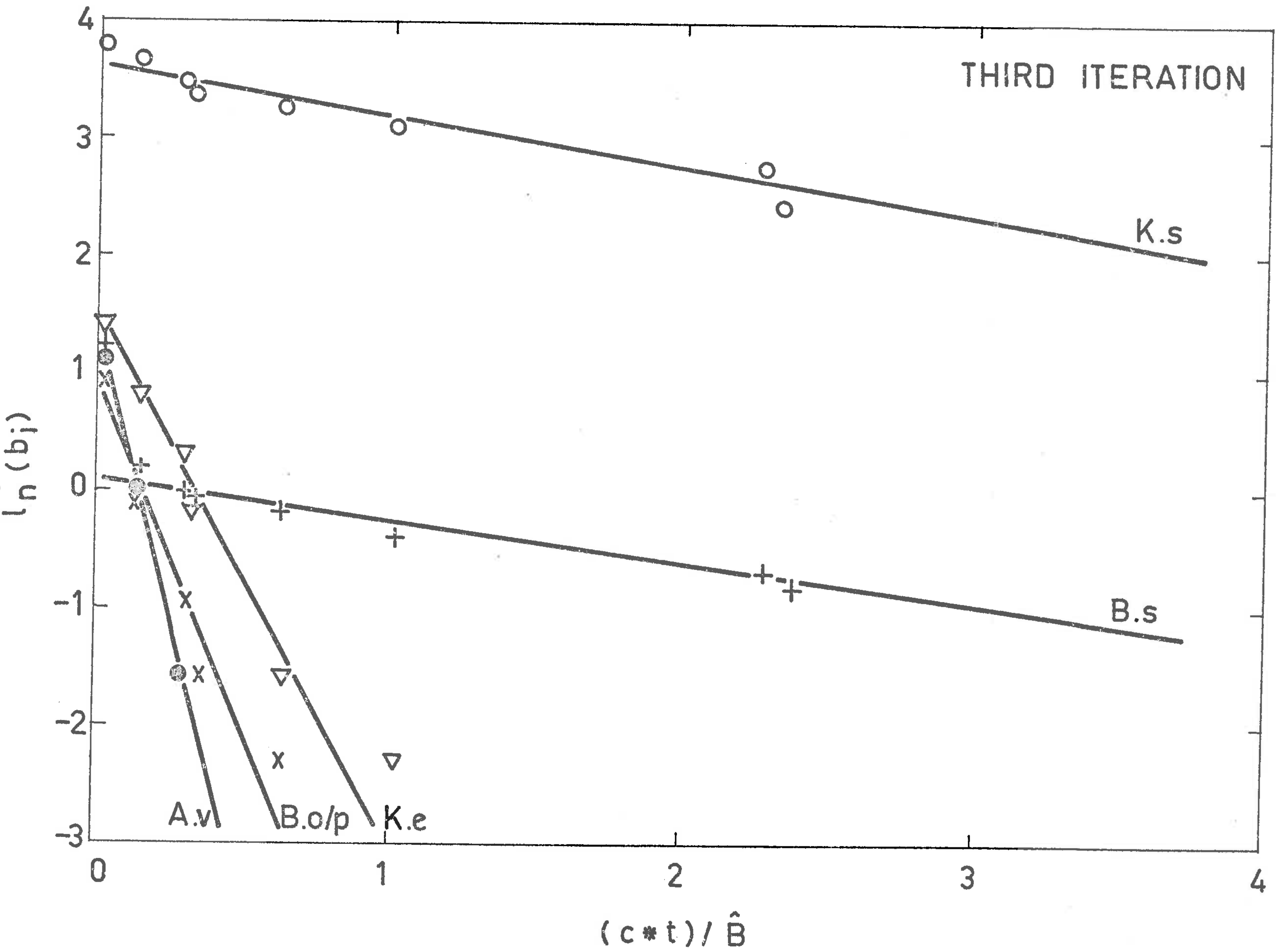


Fig. 7.6. The final iteration for the May 1973 trial.

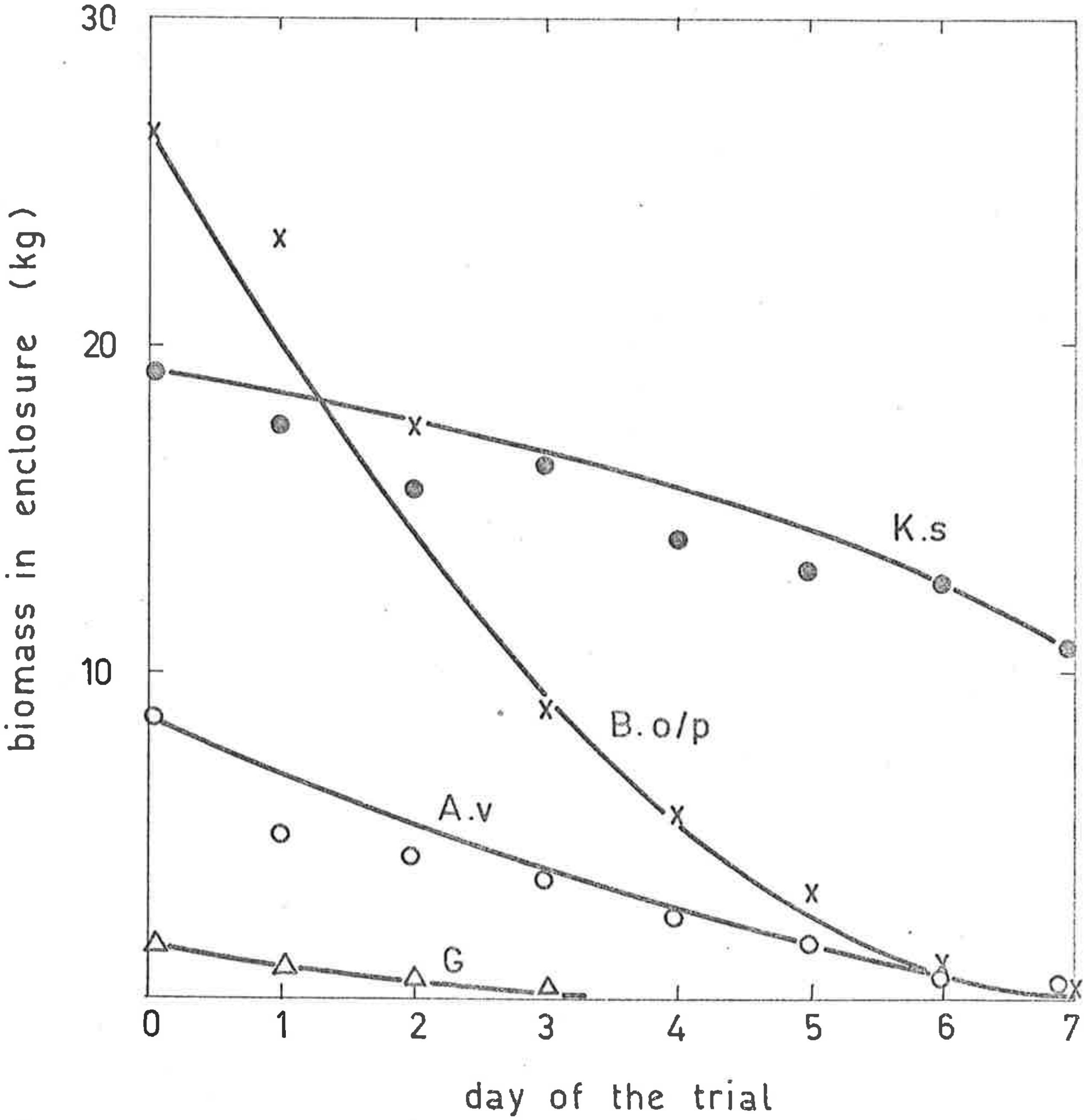


Fig. 7.7. The verification of the grazing model. The symbols represent the November 1972 data, while the solid lines represent the model output.

The indices tested by Krueger (1972).

(1) $(f_r * r) / (f_p * p)$

(2) r/p

(3) $(f_r * r) / (p * 100)$

(4) $(r * 100) / (f_p * p)$

Notation as used above and throughout chapter 7.

A_i ... availability of species i.

B ... total biomass on offer, i.e. $\Sigma\ b_i$.

B_0 ... initial total biomass.

b_i ... biomass of species i on offer.

C ... total consumption, i.e. $\Sigma\ c_i$.

C^* ... maximum consumption rate.

c_i ... consumption of species i.

c_{ij} ... consumption of species i by species j.

E ... 'effective biomass'.

f_{ij} ... consumption of species i by species j per unit time of active search.

f_p ... frequency in food on offer.

f_r ... frequency in diet.

g ... mean time to consume the forage found.

g_{ij} ... maximum consumption of species i by species j per unit time of active search if the amount of i is not limiting.

H ... height of pasture.

N_j ... density of species i.

p ... proportion of species i in food on offer, i.e. b_i/B.

p_i ... preference rating for species i; defined as $p_i = \pi_i * W_i$.

P_j ... proportion of time spent grazing by species j.

r ... proportion of species i in diet selected, i.e. c_i/C.

T ... time spent grazing.

t ... time.

w_i ... mean amount consumed at a 'successful' encounter.

π_i ... probability that species i will be consumed on being encountered.

τ ... mean search time.

Table 7.1. The notation used in chapter 7.

November 1972 dry weights (kg in enclosure)

	0	1	2	3	4	5	6	7
Bassia spp	26.6	23.3	17.5	8.9	5.7	3.3	1.0	0.3
Atriplex vesicaria	8.6	5.0	4.4	3.6	2.4	1.5	0.9	0.3
Kochia sedifolia	19.2	17.5	15.6	16.3	14.0	13.0	12.6	10.7
grasses	1.6	1.0	0.7	0.4	0.1	0.1	0.1	0.1
minor species	1.1	1.1	1.1	1.1	0.9	0.7	0.7	0.5
total biomass	57.1	47.9	39.3	30.3	23.1	18.6	15.3	11.8
consumption		9.2	8.6	9.0	7.2	4.5	3.3	3.5

May 1973 dry weights (kg in enclosure)

	0	1	2	3	4	5	6	7
Bassia obliquicuspis/ patenticuspis	2.8	1.0	0.4	0.2	0.1	0.0	0.0	0.0
B. sclerolaenoides	2.9	1.2	1.0	0.9	0.8	0.7	0.5	0.5
Atriplex vesicaria	3.3	1.0	0.2	0.0	0.0	0.0	0.0	0.0
Kochia sedifolia	45.2	39.4	34.1	31.3	27.4	22.7	15.7	11.3
Kochia excavata	3.9	2.3	1.3	0.8	0.2	0.1	0.0	0.0
minor species	1.4	1.1	0.9	0.6	0.4	0.4	0.3	0.3
total biomass	59.5	46.0	37.8	33.8	28.9	23.9	16.5	12.1
consumption		13.5	8.2	4.0	4.9	5.0	7.4	4.4
litter	(1.0)	1.4	2.3	2.1	4.0	3.3	(13.6	8.0)

Table 7.2. The results of the three grazing trials discussed in chapter 7.

January 1973 dry weights (kg in enclosure)

	0	1	2	3	4	5	6	7
Bassia obliquicuspis/ patenticuspis	7.1	4.4	3.8	2.5	0.8	0.4	0.2	0.1
Bassia uniflora/biflora	5.1	1.5	0.5	0.0	0.0	0.0	0.0	0.0
Atriplex vesicaria	13.0	8.9	7.4	5.3	3.9	1.9	0.5	0.0
Kochia spp.	3.7	3.8	3.0	2.3	1.6	0.6	0.1	0.0
Schismus barbatus	0.5	0.3	0.2	0.1	0.1	0.1	0.0	0.0
Stipa nitida/Danthonia caespitosa	1.2	0.9	0.7	0.7	0.5	0.4	0.3	0.2
minor species	0.3	0.3	0.3	0.3	0.1	0.1	0.0	0.0
total biomass	30.9	20.1	15.9	11.2	7.0	3.5	1.1	0.3
consumption		10.8	4.2	4.7	4.2	3.5	2.4	0.8

Table 7.2 continued. The results of the three grazing trials discussed in chapter 7.

	Nov 1972	Jan 1973	May 1973	Nov 1972	Jan 1973	May 1973
Bassia obliquicuspis/ patenticuspis	1.34	1.19	0.73	1.00	1.00	1.00
Bassia uniflora/ biflora		12.40			10.42	
Bassia sclerolaenoides			0.06			0.08
Kochia sedifolia	0.20		0.08	0.15		0.11
Kochia spp.		0.80			0.67	
Stipa nitida/ Danthonia caespitosa		0.60			0.50	
Schismus barbatus		3.60			3.03	
grasses	2.07			1.55		
Atriplex vesicaria	1.00	1.00	1.00	0.75	0.84	1.37

The values of p_i derived as described in section 7.41 and figures 7.4, 7.5 & 7.6. The values on the left are expressed relative to *Atriplex vesicaria* equal to 1.00, and those on the right relative to *Bassia obliquicuspis/B. patenticuspis* equal to 1.00.

bassia	1.25
grass	3.00
standing dead	0.50
Atriplex vesicaria	1.00
Kochia sedifolia	0.10

The values of p_i used in the consumption model.

Table 7.3. The derivation of the p_i values used in the consumption model.

SHEEP MOVEMENT AND BEHAVIOUR

8.0 *Introduction*

Sheep movement behaviour has been relatively little studied compared with the physiological, nutritional and even the forage selection data available. Most grazing models have been point models, but this is an unsatisfactory approach for an arid zone paddock where the utilization varies enormously from place to place. Goodall (1967, 1969) dealt with sheep movement in his grazing model by ascribing to areas an inherent potential utilization which is modified by the amount and distribution of edible biomass. All other published models, known to the author, have been point models.

There are two major impedements to modelling the varying degrees of utilization in a paddock. The first is the poor understanding of the behaviour and movement patterns of sheep flocks. The second is the cost, in computing time, of calculating the sheep movement patterns. Such a model requires a large number of separate point models so that the movement can be modelled in sufficient spatial detail. The movement may also need to be calculated on a shorter time scale than the rest of the model, and the flock may have to be considered as a number of independent subflocks. The many factors affecting sheep movement are, themselves difficult and time consuming to simulate.

Nevertheless, a movement submodel, is still essential in a realistic arid zone paddock model (section 3.3). It was initially proposed that a model should be described and a program written. This program could be run for a series of selected situations and, on the basis of its output, a simpler, empirical version could be proposed and simulated. It eventuated that the complete movement model was fast enough to be included in the full grazing model.

8.1 *A review of work related to sheep movement behaviour*

This topic has been reviewed by Hafez et al. (1969) in an article dealing mainly with the northern hemisphere literature on sheep and goats. Lynch & Alexander (1973) reviewed the literature on sheep and cattle behaviour relevant to the Australian pastoral industries. This section summarizes the points relevant to the sheep movement and behavioural model.

The sheep flock is obviously an important unit in the behaviour of a social animal such as sheep. Crofton (1958) showed that, in a flock under study, the sheep tended to arrange themselves so that two other sheep, or some other objects subtended an angle of approximately 110° in the field of vision. This was maintained during grazing and was apparently a mechanism for maintaining contact while spacing the flock. It is difficult to see what effect this mechanism has in sheep grazing in bluebush country, where the field of vision is reduced by the bushes. Merino sheep form flocks ranging in size from many hundreds to two or three animals. These groups may be observed to be continually breaking up, merging and reforming. In Australian conditions there is little evidence of home range behaviour in large paddocks (Lynch, 1967), or of dominance areas as reported by Grubb & Jewell (1966) in Soay sheep. Nor have matriarchal groups, as described by McBride et al. (1967), been seen in Australia. Flocks do show a resistance to separation and, as observed by Scott (1945), appear to follow any sheep which takes the lead in a major movement activity.

Dudzinski & Arnold (1967, 1969) measured the interaction between individuals within flocks in western N.S.W. from aerial photographs. They found the mean flock size varied from 4 to 18 depending on the paddock and environmental conditions. The flock size decreased in stress conditions, although the individual interactions as measured by distance between nearest neighbours, was unaltered.

The flocks tend to move in a daily cycle. Grazing usually commences at about dawn and ceases soon after dusk, often with a rest period in the middle of the day (Arnold, 1963; Bowns, 1971; Squires, 1971). Many studies have shown that the time spent grazing each day varies with the weather, the condition of the sheep, food availability and food quality (Arnold, 1960, 1962, 1964; Allden, 1962, 1970). It appears that night grazing occurs but it is difficult to assess its importance. Sheep vary in their choice of camp sites and shelters, according to the weather conditions. Fence lines, higher ground and tree clumps are the most common sites. In small paddocks the corners are often preferred, especially if a neighbouring flock camps nearby. The reaction of sheep to cold and their method of sheltering is relatively well studied, due mainly to the economic importance of sheep losses, especially at lambing and shearing times (Alexander, 1961a, b; Bennett, 1972). Less is known about the reaction of sheep to heat stress in natural conditions, probably because the economic effects are less obvious. It is known that sheep will seek shade and breezes, and they are often observed standing in compact flocks with their heads down and in the shade of the other animals.

Watering behaviour is important since it imposes a strict paddock use geometry. Lange (1969) described the zone around a water-point, subject to heavy grazing, as a "piosphere". In saltbush country sheep may need to water two or even three times a day, whereas in cool weather, with green forage available, sheep can maintain themselves without drinking (Lynch et al., 1972).

Travelling is a major component of sheep activity in arid zone pastures since the water-point and the preferred grazing areas are often widely separated. In northern hemisphere temperate conditions sheep travel 2 to 4 km day^{-1} (Tribe, 1949; Creswell, 1960), while in Australian conditions this may be increased to 8 km day^{-1}. Squires (1970), Squires & Wilson (1971) and Squires et al. (1972) studied the walking behaviour between food and water in a fenced race, and found that Merino wethers would walk up to 13.7 km day^{-1}. This type of travelling is usually directed along tracks radiating from the water-points. These tracks are laid with remarkable accuracy and deviate from the radial by only a few degrees over long distances (Lange, 1969). The tracks are apparently not used once the sheep start grazing.

There is evidence that sheep and cattle do not properly explore new paddocks (McBride et al., 1967), and that they will habitually graze and shelter in particular areas even though better sites may be nearby (Lynch, 1973; Schmidt, 1969). Some would argue that this tendency is reinforced by attachment behaviour, whereby certain behavioural responses become linked to particular environmental stimuli, e.g. grazing on reaching a certain site (Cairns, 1966). Graziers often describe the difficulty in shifting sheep from one water-point to another in the same paddock. Groups of sheep will continue to return to the original water-point for many days. Nichols (1944) reported similar observations.

8.2 *Sheep observations in Wertigo*

In order to gain a better understanding of the movement and behaviour of sheep flocks in Wertigo, a series of observations were made from 1972 to 1974. These were usually done during spare time while grazing experiments (section 7.30) were being carried out, or during student course work held at Middleback Station. Sometimes the other experimental site was as much as 20 km from Wertigo and the time available was limited, so the design of the observation programme was restricted.

Wertigo was chosen as the study paddock partly for its flatness and open country. It was originally intended that a separate, radio telemetry study of sheep movement would be made in Wertigo by other members of the department, but this did not eventuate. Instead, I made observations from a vehicle in a manner similar to some African studies of native and domestic animals (Young, 1972; Blankenship & Field, 1972; Jarman & Jarman, 1973). The vehicle caused little disturbance among the sheep. Sometimes a flock would run away from the vehicle but they rarely moved more than 100 m and they usually quickly resumed their previous activity. Flocks tended to be more easily frightened while they were grazing, and especially if kangaroos were nearby. Kangaroos were counted on most occasions, although it was difficult to get accurate counts, since they moved about the paddock much more quickly and fightened very easily. The sheep became used to the vehicle and by about the third day of observations they rarely fled even on a very close approach, as, for example, when a flock straddled the track.

It was not possible to conduct 24 hour watches as have been used in studies of other animals. Instead the vehicle tracks of the paddock and adjoining paddocks were traversed at times which were both suitable for observation and convenient. The most suitable times varied with the weather and season, but usually a mid to late morning observation (9.00 to 11.00 hrs.) and a late afternoon observation (15.00 to 19.00 hrs.) were the best, since these were the times when most of the sheep were grazing, and their previous position and probable destination could be inferred.

The position of the groups of sheep, the approximate numbers in each group, their activity and their direction of movement were recorded on maps of Wertigo paddock (fig. 8.1). This was repeated 2 to 5 times per day, at times varying from first light to darkness. Air temperature, wind direction and approximate force, and cloudiness were also recorded. The observations were backed up by sheep track and water-point sweepings. The soil in Wertigo forms a very fine dust when swept and the movement of sheep over swept areas shows very clearly. This technique was especially useful for determining whether flocks moving past a water-point had actually been in to drink.

Daily observations were continued from 5 to 10 days at the dates shown in figure 8.2. These observations usually supplied enough data to infer the generalized daily movement patterns of the flocks. During the period of study the sheep were shifted from the trough to the dam water-point, so activity patterns based on two different foci were obtained.

The inferred daily movement cycles are shown in figure 8.3. The bulk of the flock followed these patterns, however some sheep followed radically different patterns. The daily cycles were similar to those described elsewhere, i.e. a morning grazing period starting at about dawn, followed by a middle of the day rest period and then a second grazing period (Arnold, 1962; Bowns, 1971; Squires, 1971). In cool weather this second period could occur in the early afternoon with a third period of grazing in the evening, whereas in summer the rest period usually extended from late morning to late afternoon, with a second grazing period in the evening.

The sheep were observed in flocks varying from 2 to 480 individuals. Usually the smallest unit was 8 to 20 sheep, and often 12 to 15 sheep. Several groups of this size were often found near each other in an elongated flock. The splitting of one group into two or more smaller flocks was observed on several occasions. Figure 8.4 shows one such occasion. This process of splitting and regrouping often occurred several times during the day, sometimes with the transfer of sheep from one flock to another. The sheep tended to form smaller flocks, and to spread over wider areas in hot weather. This was probably a mechanism to allow more complete searching for scarce palatable ephemeral plants.

Five camp sites were found in Wertigo. Camp sites and major shelter sites were distinguished by the dung accumulations. Some shelter sites were not camp sites. Sheep would walk past a shelter site they had used even on the same day, and go to a camp site further away. Many evenings the sheep continued to graze later than they could be observed from the vehicle. On several occasions flocks were followed on foot until they reached a camp site. The sites were usually near tree groves, but one was in the open in the corner of a paddock (fig. 8.5). The sheep often rested on the dam but rarely camped at either of the water-points, although there was one camp site in some trees near the dam.

The sheep usually took shelter from the heat near an isolated tree or small group of trees. Often only a part of the group using the trees could fit in the shade, while the rest stood in the compact groups described above, and shaded their heads. Those on the outer edge of the flock would have had the advantage of whatever breeze was blowing. In cooler weather the sheep normally rested by laying down anywhere in the paddock, although a few moved to a tree clump if one was nearby. On several occasions, the sheep were observed during rain. They showed little reaction to light rain, and usually continued their previous activity. In heavier rain they often moved into more compact flocks.

Sometimes they moved to a nearby tree even though the shelter given by the tree was often inadequate for all but a small section of the flock.

The rate of movement while grazing varied from almost zero to 1.0 km hr^{-1}. On several occasions the speed of sheep moving to or from water and not grazing, was measured and was found to be about 2.5 km hr^{-1}. This is within the range of 2.4 to 2.7 km hr^{-1} reported by Squires et al. (1972) for merino sheep moving to or from water.

8.3 *Other models of animal movement and dispersal*

The study of the dispersal (or diffusion) of animals from a point site, or sites, is important in many fields of ecology and has been well investigated by traditional mathematical methods. The mathematical techniques are described by Skellam (1951) and Pielou (1969, chpt. 11), and the experimental and observational techniques by Andrewartha & Birch (1954). The majority of this work has dealt with insects dispersing from point sites and seeking new sites. Traditional mathematical techniques soon prove to be inadequate when field reality is added to the theoretical dispersal models.

The small amount of work on migratory studies has relied heavily on diffusion and random walk theories. Saila & Flowers (1969) used a heat diffusion analogy to describe fish movements, while Wilkinson (1952) described bird navigation via a modified random walk process.

Several computer models of animal movement has been published. Kitching (1971) described a general model of animal dispersal from a point site to other potential habitats. This model could be expanded as further information becomes available. Siniff & Jessen (1969) described a model of animal movement based on a random walk process. They used their model to study the effect of different assumptions about animal movement on the resultant home ranges.

The majority of the work carried out on mammal movements has been in terms of home range size and shape. This work has been reviewed by Sanderson (1969). He was critical of the emphasis placed on home range and argued that more emphasis should be placed on why an animal is in a particular position at a particular time. This is essentially the problem that must be solved in the sheep movement model. It appears that no other models of the same detail as the one to be described in this chapter have been reported.

8.4 *The Movement Model*

The problem, at this point, was to build a model that was fast to execute and easy to modify, but which gave an adequate description of sheep movement around a paddock. This model was to be based on the data summarized above. Simple random walk or diffusion models were regarded as inappropriate since they are unable to account for the detailed variation in behavioural patterns due to paddock heterogeneity and environmental variablility. The model, at least initially, must be considerably complex, although it might possibly be simplified later. No behavioural model of similar detail has been published and therefore, many new approaches and assumptions had to be made.

It was decided to model the movement of small flocks (or subflocks) of 10 to 20 animals, which are assumed to remain together and to show similar behavioural patterns during the day. The main flock is divided into a number of equal sized subflocks, and each subflock is represented by a 'standard sheep'. The use of a standard, or average, sheep seems reasonable in view of the observation that sheep tend to follow a leader or leaders. The leader may vary from activity to activity but the behaviour of the subflock tends to be synchronized. Subflocks were observed moving to water in a single group, resting at the same time and grazing at the same time. Grazing activity is not continuous for each individual but a subflock grazing is easily distinguished from one resting. Sheep were observed moving from one subflock to another during the day, and more transfer probably occurred whenever subflocks came together in shade or campsites. Given the lack of evidence of matriarchal groups or home ranges (section 8.10), it must be realised that the subflock is probably only an artificial concept, useful in describing the observed contagation of sheep while grazing.

The main behavioural functions are divided into 8 mutually exclusive activities (table 8.2). They bear no direct relationship to the 9 general behavioural functions described by some animal behaviourists (e.g. Scott, 1958), but are more directly related to the needs of the model.

A subflock grazing includes many individuals which are resting, ruminating or engaged in some other activity. However, the majority will be grazing and the subflocks will show a typical grazing distribution and rate of movement across the paddock. A subflock resting (which includes ruminating) may include a few animals grazing but the majority will be standing still or lying down. The resting subflock tends to be more compact, and shows no net movement.

If the flock moves to a particular site before resting, the model describes this as camping, sheltering or as watering behaviour. Sheep only move to a camp site after sunset and if they happen to be sheltering at a camp site during the day, this is called sheltering behaviour. It is assumed that all the sheep sheltering are actually in the shade, although it is recognised this is not always the case.

The other major set of activities is travelling to camp, shelter or water. These could be regarded as being essentially the same activity, with different destinations. However the state of the sheep varies with each, e.g. sheep travelling to water are thirsty and possibly hot as well, whereas sheep travelling to camp may be under no stress at all. It is also simpler in the structure of the model to consider them as separate states.

The model does not allow for grazing while travelling to a destination. Flocks were observed grazing in the general direction of water or shade. This is probably a case of directed grazing activity, rather than travelling, and is associated with learning factors, e.g. a knowledge of the best grazing sites, or the realization that night is falling or the hottest part of the day is approaching and grazing activities should be modified appropriately, and so on. Such factors could be added later (as proved necessary in section 8.8420).

The model operates on an hourly time step. This represents a compromise between realism and cost in computing time. During each time step the flock is assumed to show only one activity and this can be changed only on transition to the next time step. This means that all activities continued for at least one hour. This is a suitable approximation for grazing, resting and camping, but is probably too long a time step for some travelling and drinking activity. These activities could have been modelled on a shorter time step but this would lead to a major increase in programming complexity.

The next step in the building of the model was to describe the conditions causing the transition from one activity to another. The transition is dependent on the previous activity, changes in the external environment such as nightfall or high temperatures, and changes in the sheep itself, such as increasing thirst or hunger.

The most usual approach to this type of problem would be as outlined in figure 8.6. This section of the flow chart shows the different decisions that have to be made at each time increment. There is much repitition in the flow chart shown and this could be reduced in the computer program, but only at the cost of making it very hard to modify and debug.

A more logical approach is that of a symbol-state table (or transition matrix) (see Day, [1972] for a summary of their computing aspects). In this approach the transitions from one activity to another are controlled by a series of trigger conditions. These triggers describe whether the sheep is hot, thirsty, hungry and so on. In this model a special case is used, where the triggers are in an absolute heirarchy. A table was set up with an entry for each activity-trigger pair. (table 8.3). At each time increment, the program performs the calculations to set those triggers appropriate to the environmental conditions and the condition of the sheep. These calculations are described below. The highest, set trigger in the heirarchy is then determined and the table value for the particular trigger-previous activity pair is obtained. This value indicates the activity for the next time step.

This approach has many programming advantages. It is simple to execute, requiring only 2 FØRTRAN statements rather than a complicated set of logical statements; for example,

```
      IT = MAXO (ITR1, ITR2, ...., ITR7)

      IACTVTY = ITABLE (IT, IACTVTY)
```

or some equivalent coding to determine the most important trigger set and take a value from the table. The table is readily modified, since this only requires changing an entry or inserting or deleting a row or column. This can be programmed so that it can be carried out during the program execution (e.g. interactively) without re-compilation and re-loading.

This approach is a special form of a decision table, a method which has wide application throughout systems analysis (Dixon, 1964). Its use in simulation has been discussed by Davies (1974), although only in the context of discrete-system simulation. A modified version of the transition matrix actually used in the model is shown for comparison in a decision table form in table 8.4. This does not include the travelling activities since these make the table much more complex.

The triggers included in the model are listed in table 8.2. Two levels of each of thirst and heat stress are included. The heat stress levels corresponded to being hot, i.e. when the respiration rate required to maintain a normal body temperature is above an acceptable (comfortable) limit; and very hot when the body temperature can not be maintained by increasing the respiration rate, and is allowed to rise. Two levels of water stress are included to allow for a realistic treatment of sheep under both heat and water stress. In hot weather sheep were observed in Wertigo to travel to drink, and then immediately to travel to nearby shade, indicating that they were under both heat stress and water stress, but the water stress dominated their behaviour. However, it is argued that, in very hot conditions sheep would probably remain in the shade, rather than walking in the sun to the water-point and having their body temperature rise. Partial confirmation of this point was seen in Wertigo, in that sheep did not normally drink in the hottest part of the day (i.e. mid to late afternoon), but instead they waited until the air temperature and solar radiation load began to decrease rapidly after about 16.00 hrs. C.S.T. This type of activity pattern can be explained by the triggers 2, 3 and 4. The 'dehydrated' trigger is included to account for those times when sheep had suffered such water losses that deleterious physiological reactions were occurring and hence it is preferable that they drink immediately even if this means a rise in body temperature. Although these triggers may appear arbitrary, they logically describe the behavioural responses that affect the sheep movement around the paddock, and the concomitant removal of biomass through grazing.

The two remaining triggers are nightfall and hunger. It is assumed in this model, that night grazing is insignificant, hence the nightfall trigger dominates the hunger trigger. Nightfall is defined as occurring in the second hour after the hour of sunset, and as lasting until the hour of dawn the next day. This correlates with the observed camping behaviour in Wertigo.

The evaluation of the triggers is a major task in itself. The heat and thirst stress triggers require complete thermal and water balance of the sheep submodel. This model also calculates the time of sunrise and sunset and hence includes the nightfall trigger as well. It is described in sections 8.410 to 8.416 while the hunger submodel is described in sections 7.43 and 8.420.

8.410 *The thermal and water balances of a sheep*

This section describes the construction of a model of the thermal and water balances of a sheep. The term 'thermal balance' is used to distinguish the study from a complete model of the physiological and nutritional energy balance of a sheep. The thermal balance deals with the factors affecting thermal comfort and their interaction with the water balance.

8.411 *Other animal thermal balance models*

The thermal balance of a sheep was described by Lee (1950) and by Priestley (1957). They suggested that their models might be used as a framework for experimental design and analysis. Porter & Gates (1969) calculated the thermal balances of a number of different animals and presented their 'climate diagrams', i.e. "the climate space which any animal must occupy in order to survive." They argued that is was possible to predict from the climate diagrams, the environmental conditions which would force the animals to move to more favourable conditions. This occurred when the normal physiological, adaptive mechanisms could no longer maintain tolerable body temperatures and behavioural correction was needed. Lee (1972) discussed thermal stress and strain, i.e. the disturbance experienced by an animal exposed to hot conditions. He expressed this in terms of the actual evaporative cooling rate compared with the maximum attainable by the animal. Ojo (1971) constructed a model of the cattle thermal load and used this as an indicator of the potential animal productivity in Nigeria.

Several studies have followed Porter & Gates' (1969) approach. These have estimated the thermal load of animals in a particular environment and have compared this with the observed animal behaviour. Bartlett & Gates (1967) described the thermal balance of a lizard on a tree trunk and correlated it with the observed position of the lizard. Zervanos & Hadley (1973) included a thermal model in their study of the energy requirements and vegetation intake of the collared peccary in Arizona. Morhardt & Gates (1974) investigated the time available for grazing and the shelter requirements of a ground squirrel via a thermal load model. Spotila et al. (1973) demonstrated, by the use of a model, that gigantism would have been a very useful strategy for reptiles during the equitable climate of the Mesozoic era. The above models have been concerned mainly with the thermal balance of the animal, and only indirectly with the behavioural effects. The most complete thermal balance -

behavioural study is that of Porter et al. (1973). They modelled the environment and the thermal load of an iguana in order to predict its behaviour and water requirements, and to demonstrate that such studies are important in predator-prey interactions.

In Australia, Kitchener (1972) correlated the movement of quokkas from one shade site to another, with changes in the thermal load beneath the bushes. Dawson & Denny (1969) studied the thermal environments of the red kangaroo and euros in arid areas. They found that the preferred shelter changed as the factors contributing to the thermal load varied during the day. Dawson (1972) investigated reports that kangaroos vary their pasture during the course of the day. None of the Australian studies have included a thermal load model.

The above studies have provided guidelines to building thermal models and their effect on behaviour, but none have attempted the detailed hour to hour interactions between the thermal load and other behavioural determinants.

8.4120 *The sheep thermal balance model*

The merino sheep has long been recognised as being efficiently adapted to the arid zone (Macfarlane, 1964). Basic physiological work has been reported by Graham et al., (1959); Blaxter et al., (1959a, b); Macfarlane et al., (1956, 1958); Macfarlane et al., (1961); Macfarlane et al., (1966). Lee (1950) outlined a model of the thermal balance of a sheep standing in the sun, and this was extended by Priestley (1957). Porter & Gates (1969) included the sheep among the animals for which they presented a climate diagram.

A model of the energy balance of a sheep may be based on the first law of thermodynamics, whereby energy inputs at any point must equal energy outputs. For a sheep, this may be stated as,

(E8.1) Radiative exchange + convective exchange + conductive exchange + evaporative exchange + metabolic heat production - storage = 0.

In this model the sheep is approximated by a section of an insulated cylinder and the end effects of the cylinder are ignored (fig. 8.7). Similar approximations have been used by Priestley (1957) and Porter & Gates (1969). Porter & Gates also included a second layer of fat insulation, but this is omitted in this model since the insulative value of fat is much less than that of wool, and this layer would often be thin in arid zone sheep. The wool is considered to be of uniform staple length over the body of the sheep (Doney, 1959). The major components in the heat balance are shown in figure 8.7.

The thermal balance is evaluated by calculating the temperature of the outer surface of the wool by the equation (see table 8.1 for the meaning of the symbols),

$$R_s + R_{sky} + R_g - R_b \pm C_a \pm C_f = 0. \qquad \text{(E8.2)}$$

The conductive term can then be evaluated and the net heat gain or loss to the body is,

$$ME \pm C_f - EV = 0. \qquad \text{(E8.3)}$$

This equation is solved by adjusting the respiration rate which is part of the EV term. The respiration rate is used as an index of thermal stress and to calculate the water losses.

The next 10 sections describe the evaluation of the various heat transfers and the solutions of the equations. The heat transfers have been derived from a mixture of standard physics and engineering equations and experimental results. It was intended that the model be applicable to sheep of any size or breed at any locality, so the equations were derived initially in their general form. However, in order to reduce the computing time needed for their evaluation, equations applicable to mature wethers in Wertigo have been used in the model.

8.4121 *Short wave radiation*

Short wave (solar) radiation is an important component of the heat input to most organisms. Its magnitude varies regularly during the course of a day and of a year, and is further modified by atmospheric fluctuations such as cloud cover and dust. Only rarely are sufficient data collected to allow an empirical model of its contribution to the heat load of an organism to be built.

The geometry of the annual and diurnal variation of solar radiation has been described in many texts, and specifically for application in biological models by Berry (1964), McCullough & Porter (1971) and Harris (1972) among others. These models vary in their detail and accuracy. The following set of equations, derived from the above sources, allow the direct solar radiation on a horizontal surface above the atmosphere, Q_A, to be calculated for any time of day and date for any latitude.

(E8.4) $$Q_A = Q_0 * \sin(\alpha) / r^2$$

(E8.5) $$1 / r^2 = 1 + 2 * \varepsilon * \cos(360 * D / 365)$$

(E8.6) $$\sin(\alpha) = \cos(\phi) * \cos(\delta) * \cos(h) + \sin(\phi) * \sin(\delta)$$

(E8.7) $$\delta = 23.5 * \sin(360 * [D - 80] / 365) \quad \text{... degrees}$$

(E8.8) $$h = -15 * (t - t_{noon}) \quad \text{... degrees}$$

The equations refer to a latitude of ϕ degrees, on the D^{th} day of the year at t hours; α is the solar altitude and δ is the solar declination. The time of the true solar noon, t_{noon}, at Middleback varies from 12.05pm to 12.35pm Australian Central Standard Time (C.S.T.) depending on the equation of time for the particular date. In this model a t_{noon} of 12.3 hours (12.18pm) has been used for all dates. The units of Q_A are determined by Q_O, the solar constant.

The solar radiation is attenuated as it passes through the atmosphere. The attenuation is dependent upon the depth of the atmosphere traversed, usually expressed as the air mass number, m. For $\alpha > 10^o$

(E8.9) $$m = \operatorname{cosec}(\alpha)$$

and for $10^o \geqslant \alpha > 2^o$,

(E8.10) $$m = (\sin[\alpha] + 0.025 * \exp[-11 * \sin[\alpha]])^{-1}$$

(McCullough & Porter, 1971). Although the simpler equation underestimates the solar radiation by about 10% for $\alpha < 10^o$, this only results in a maximum absolute error of about 5 W m^{-2}, and so the simple equation has been used for all α.

The absorption and scattering of the direct solar beam is a complex process involving the scattering due to the pure atmosphere, a scattering contribution due to dust and absorption by water as its main components. The most accurate description is the Ångstrom turbidity formula (Robinson, 1966), however most of the necessary variables are not available for the Middleback area.

The equivalent optical path length for the absorption by water vapour and the scattering effects in the air is proportional to m, and Beer's Law can be used to calculate the approximate, direct plus diffuse solar radiation on a horizontal surface;

$$\text{(E8.11)} \qquad Q \,/\, Q_A = \exp(-k' * m)$$

where k' is a constant depending on the dust and water vapour in the atmosphere. This relationship is often expressed as,

$$\text{(E8.12)} \qquad Q \,/\, Q_A = (\exp[-k'])^m = k^m.$$

Trewartha (1954) suggested that $k=0.78$ was a suitable value for many sites. Most clear atmosphere measurements give $k \simeq 0.8$. Hounam (1963) showed that for Australian clear skies, $k=0.90$; an exceptionally high value.

The diffuse radiation varies with the solar altitude, atmospheric composition and cloudiness. It can contribute from 5% to 100% of the global radiation. McCullough & Porter (1971) demonstrated that for a pure Rayleigh atmosphere, the diffuse radiation is related to the direct radiation for a given surface albedo. They presented a graph for a surface albedo of 0.25, the albedo commonly used for sandy and dry soils. In these conditions the diffuse radiation is less than 10% of the direct radiation for solar altitudes of greater than 30°. In this model,

(E8.13) $$\text{diffuse radiation} = 0.08 * Q$$

is used for all solar altitudes. This results in a maximum relative error (according to McCullough & Porter's chart) of 10% and a maximum absolute error of about 14 W m^{-2}.

The diffuse radiation at a point does not come evenly from throughout the sky hemisphere. Brooks (1960) suggested that 45% of the diffuse radiation came from a small cone near the sun, and may be considered similar to direct radiation, while the other 55% may be considered to be evenly distributed over the sky. This is used in the model.

8.4122 *Short wave radiation absorbed by a sheep*

The radiation falling on a sheep is calculated by considering the sheep to be a cylinder. The end effects are ignored and it is assumed that the sheep minimizes the radiation load by orienting the long axis of its body towards the sun. The direct solar radiation falling on the curved surface of a horizontal cylinder of length L, and radius R, is $2 * R * L$, while the diffuse radiation is, $\pi * R * L$. The total direct plus diffuse radiation is calculated as,

$$\begin{aligned}\text{short wave radiation load} = {} & 0.92 * Q * 2 * R * L + 0.08 * \\ & Q * (0.45 * R * L + 0.55 * \\ & \pi * R * L)\end{aligned}$$

(E8.14) $= 2.01 * Q * R * L.$ ... W

The radiation reflected from the ground must also be taken into account as an additional heat load. This is considered as a diffuse source with a flux of,

(E8.15) $\text{flux} = alb_g * Q$

where alb_g is the albedo of the surrounding surface, in this case taken to be 0.25. However a part of this potential diffuse source is shaded by the sheep. This varies from $^1/_3$ of the solid angle at noon, to near zero at dawn and dusk. It is assumed that $^2/_3$ of the ground surface is reflecting solar radiation after allowing for the sheep's shadow and other shadows. The reflected short wave radiation load is therefore,

$$\text{reflected short wave radiation} = (^2/_3) * alb_g * Q * \pi * R * L$$

(E8.16) $= 0.52 * Q * R * L,$

and the total short wave radiation load is,

(E8.17) $= 2.53 * Q * R * L.$

The solar radiation absorbed at the wool tip is,

(E8.18) $= (1 - alb_s) * 2.53 * Q * R * L$

where alb_s is the albedo of the wool tip. The albedo varies from 0.42

in new shorn sheep to 0.26 in older fleeces (Blaxter, 1962). In the arid zone fleeces become dirty very quickly after shearing, so the value of 0.26 is used throughout the model.

In this model it is assumed that if a sheep moves into shade, then no direct solar radiation reaches the sheep, and only ¼ of each of the diffuse and reflected ground solar radiation reaches it. The total solar radiation loads are,

(E8.19) in the sun $= 1.87 * Q * R * L$ ... W

(E8.20) in the shade $= 0.17 * Q * R * L$. ... W

Another important factor to be considered is cloud cover. A deep layer of stratus cloud will transmit as little as 10% of the direct solar radiation, while a thin layer of cirrus cloud will transmit up to 70% (Monteith, 1973). Lumb (1964) made a detailed study of the effect of different cloud layers on solar radiation in the North Atlantic, and Maine (1958) carried out a similar study for Adelaide, but both were too detailed to be included in this model. Clouds also have a minor effect on the total diffuse radiation. In this model it is assumed that the sun is either obscured by cloud or not so, and that there is no variation in cloud type. The Ångstrom equation is then used to estimate the mean transmission of solar radiation through a cloud layer. Hounam (1963, 1969) determined that for a range of Australian sites the mean empirical equation was,

(E8.21) $Q' / Q_A = 0.26 + 0.50 * n / N$

where Q' is the solar radiation actually received over a given period (in this case a year), Q_A the Angot value (i.e. the radiation received at the top of the atmosphere), and n/N is the proportion of the actual to the maximum amount of sunshine received. Black _et al._ (1954) determined that, on a daily basis for Dry Creek (near Adelaide), the equation was;

(E8.22) $$Q' / Q_A = 0.30 + 0.50 * n / N.$$

I argue that, since on a totally overcast day the solar radiation input is equal to only the constant term of Ångstrom's equation multiplied by Angot's value, then the mean transmission of solar radiation through a cloud is equal to this constant term. The solar radiation loads, using the Dry Creek estimate of 0.30 and regarding all the radiation as diffuse, are,

in the open $= 0.3 * Q * R * L * \pi\,(1.0 + alb_g) * (1.0 - alb_s)$

(E8.23) $= 0.87 * Q * R * L,$ ... W

(E8.24) under shelter $= 0.22 * Q * R * L$ ... W

This is obviously only an approximation, since it assumes that the sky is either completely covered with cloud, or completely clear.

8.4123 *Long wave radiation*

Priestley (1957) calculated the net long wave radiation loss from the fleece of a sheep to be,

$$R_1 = \varepsilon * \pi * R * L * (2 * \sigma * T_s'^4 - 1.04 * B) \qquad \text{(E8.25)}$$

where T_s' is the wool surface temperature (K), T_g' is the ground surface temperature (K), and B is the long wave sky radiation, for which he used the Brunt (1939) equation,

$$B = (0.44 + 0.08 * \sqrt{e}) * \sigma * T_a'^4 \quad \text{for } e < 22\text{mb}, \qquad \text{(E8.26)}$$

where e is the atmospheric water vapour pressure in millibars, and T_a' is the air temperature (K). The units are determined by the units of the Stefan-Boltzman constant, σ. Swinbank (1963), after examining Brunt's equation, proposed the equations,

$$B = -170.9 + 1.195 * \sigma * T_a'^4 \quad \ldots \text{Wm}^{-2} \qquad \text{(E8.27)}$$

$$\text{and} \quad B = 5.31 * 10^{-13} * T_a'^6 \quad \ldots \text{Wm}^{-2} \qquad \text{(E8.28)}$$

and recommended the use of the latter. The latter equation is used in the model since, according to Swinbank, it gave a better fit to experimental data, and since it does not require an estimate of vapour pressure.

Priestley argued that, when no better estimates were available, it could be assumed that $T_g = T_s$ and the long wave radiation equation simplified to, (E8.29) $$R_l = \varepsilon * \pi * R * L * (\sigma * T_s'^4 - 1.04 * B)$$

An emissivity of 0.98 is used for the wool surface (Blaxter, 1959a).

Monteith (1973) pointed out that in some conditions the long wave sky radiation may be increased by up to 20% due to cloud cover, although the effect was usually much less than this. It is not included in the model. It is also assumed that the under surface of a shade tree is at approximately the same temperature as the air, and therefore the longwave radiation remains the same in both cloudy conditions and in shade.

8.4124 *Convective heat transfer*

Heat is exchanged between the fleece surface and the air when there is a temperature difference between them. For low wind velocities free convection across the boundary layer occurs, while, for higher velocities, forced convection predominates. Graham et al. (1959), Blaxter et al. (1959a, b) and Joyce et al. (1966) have determined the convective losses from a sheep experimentally, while Gates (1962) derived an equation based on engineering principles;

(E8.30) $$h_c = 6.17 * 10^{-3} * (V / d^2)^{1/3} \quad \ldots \text{cal cm}^{-2} \text{min}^{-1}\,^{\circ}\text{C}^{-1}$$

where h_c is the convection coefficient, V the wind velocity (cm s^{-1}) and d is the diameter of the animal (cm) considered as a smooth horizontal cylinder orientated perpendicularly to the wind direction. It was noticed that this equation gave results of only about $^1/_5$ of the experimental values of Joyce et al. and of the table given in Priestley (1957). Gate's equation has been used in many thermal models, and since the necessary engineering equations were readily available (e.g. Holman, 1963), it was decided to examine the convective heat transfer in more detail.

In calm conditions ($V \leqslant 0.2$ m s^{-1}),

(E8.31) $$h_c = 1.138 * (\Delta T \;/\; d)^{1/4} \qquad \ldots \text{ W m}^{-2}{}^{o}\text{C}^{-1}$$

where ΔT is the temperature difference between the fleece and the air (^{o}C), i.e. $T_s - T_a$. The convective heat exchange is,

(E8.32) $$C_a = h_c * A * \Delta T \qquad \ldots \text{ W}$$

The forced convection term was derived from the equation,

(E8.33) $$h_c = k_f * c * Re^n \;/\; d,$$

where k_f is the thermal conductivity of air, Re the Reynolds number, and 'c' & 'n' are constants specific for the range of the Reynolds number. The Reynolds number is,

(E8.34) $$Re = V * d \;/\; \nu \qquad \ldots \text{ dimension-less}$$

where ν is the kinetic viscosity of air and is equal to, (E8.35) $\nu = \mu/\rho$

where μ is the dynamic viscosity of air, and ρ is the density of the air. The density of air is dependent on the temperature;

(E8.36) $\rho = k / T'_a$

where k is a constant depending on the units of ρ. Most engineering formulae are written in imperial units so these have been retained until the final calculation of h_c. Hence,

(E8.37) $\rho = 22.2 / T'_a$ ... lb ft^{-3}

The dynamic viscosity of air is usually given in tabular form, but it was found that over the range of temperatures relevant to the model,

(E8.38) $\mu = 0.0416 + 0.000108 * T_a$ ... $\text{lb hr}^{-1}\ \text{ft}^{-1}$,

Ta in °C.

Therefore,

(E8.39) $\nu = 0.512 + 0.0032 * T_a + 0.0000049 * T_a^2$,

... $\text{ft}^2\ \text{hr}^{-1}$, Ta in °C

and, in the temperature range 0 to 50°C, the second order term may be omitted.

The Reynolds number is a dimensionless number given by equation 8.34. For a sheep exposed to wind velocities greater than 2 m s^{-1}, it is in the range 40000 to 400000, and the appropriate values of 'c' & 'n' are, c= 0.0239 and n= 0.805. The thermal conductivity of air is,

(E8.40) $$k_f = 0.0138 + 0.000046 * T_a \quad \ldots \text{BtU hr}^{-1}\,{}^{\circ}\text{F}^{-1}$$

If the convection coefficient is written as,

(E8.41) $$h_c = 0.0239 * (k_f / \nu^{0.805}) * (V * d)^{0.805} / d \quad \ldots \text{BtU ft}^{-2}\,\text{hr}^{-1}\,{}^{\circ}\text{F}^{-1}$$

it may be shown that $(k_f / \nu^{0.805})$ varies between 0.0232 and 0.0219 for the temperature range 10°C to 50°C. Therefore h was assumed to be independent of temperature, and the value $(k_f / \nu^{0.805}) = 0.0227$ (i.e. for $T_a = 25^{\circ}C$) was used in all cases.

After allowing for the change of units,

(E8.42) $$h_c = 4.62 * (V * d)^{0.805} / d \quad \ldots \text{W m}^{-2}\,{}^{\circ}\text{C}^{-1}$$

where V is in m s^{-1} and d in metres. This equation was compared with the table given by Priestley for a 0.50 m diameter sheep (fig. 8.8). The results were in relatively close agreement. Joyce et al. (1966) measured the convective losses of a 0.30 m diameter sheep in an outdoor environment. Their results may be expressed in the form,

(E8.43) $$h_c = 7.17 * V^{0.5}$$

for the same units as equation 8.42. Equation E8.42, Joyce et al.'s equation, and Gates' equation were all compared for a sheep of 0.30 m diameter (fig. 8.9). It should be noted that the measurements made by Joyce et al. were based on wind velocities of up to only 7 m s^{-1}, and the wind direction was not exactly perpendicular to the long axis of the sheep.

Gates' equation gave results very much lower than either the experimental results or those of equation E8.42. However, it was realised that Gates' equation was exactly equivalent to the equation derived similarly to equation E8.42, but for Reynolds' numbers of 0.4 to 4.0, and is therefore applicable for horizontal cylinders of approximately 1 mm diameter. Equation E8.42 and the experimental results are in close agreement for low wind velocities, but varied by a factor of 2 for velocities of 20 m s^{-1}. It was decided to use equation E8.42 in the model since it contains the diameter term. As wool growth occurs the diameter of a sheep can increase by as much as 50%, so it must therefore be an important parameter. Pearman et al. (1972) recommended that the values of h_c derived from engineering equations for laminar flow, should be increased by 50% when applied to the turbulent flow in biological situations. However a comparison of equations 8.42 and 8.43 indicated that this was not necessary.

It is assumed that perfectly calm conditions do not occur, and equation 8.42 is used throughout the model rather than including equation 8.31 as well. This makes the evaluation of the heat balance much simpler, and leads to only small errors. The wind model produces 'calm' conditions, but in these cases the velocity is set to 0.5 m s^{-1}. This velocity (equivalent to 1.8 km hr^{-1}) is less than the walking speed of the sheep.

8.4125 *Conduction through the wool*

The conduction term is given by,

(E8.44) $$C_f = k * A * (T_s - T_b) / W,$$

where k is the thermal conductivity of wool, T_b the body temperature (or, more strictly, the skin temperature), and W is the wool length (m). Priestley (1957) assumed the conductivity of wool was the same as that of air; 0.042 W $m^{-1}C^{-1}$. Bennett & Hutchinson (1964) demonstrated that this value was too low, and that the conductivity was dependent on the wind speed and the wool length. However in the model, the conductivity has been assumed to be constant and equal to the mean of the in vivo estimations by Blaxter et al. (1959); 0.064 W $m^{-1}C^{-1}$, and,

(E8.45) $$C_f = 0.402 * R * L * (T_s - T_b) / W \quad \ldots \text{W}$$

8.4126 *Metabolic heat production*

The metabolic heat production may be estimated from the metabolic energy requirement for maintenance. Most of these studies have been done with penned sheep although it was realised that the requirements of grazing sheep would be higher (Blaxter, 1962; Weston & Hogan, 1973). The requirements are increased by either heat stress or cold stress and by physical activity. Graham (1964) estimated the energy costs specific to the activities of grazing, ruminating, standing and walking.

Young & Corbett (1972a) have estimated the maintenance requirement for sheep grazing pastures in cool weather. Their results may be summarized as (Vickery & Hedges, 1972),

(E8.46) $ME = 5.5 * LW^{0.75}$. ... W

This equation is used in the model. No allowance has been made for changes in the distances walked and grazing time in arid zone sheep, since on examination of Graham's figures, these would not be important except in hilly country.

When the sheep suffer cold stress, the respiratory rate does not fall below a minimum rate (here set to 20 r min^{-1}) and the extra heat is produced by raising the metabolism. The increased metabolic heat production is taken into account in calculating wool production and changes in live weight.

8.4127 *Evaporative cooling*

Evaporative cooling occurs in the respiratory tract during respiration and from the skin surface as sweat. Estimates of the absolute and relative amounts of respiratory and sweat cooling vary. Macfarlane (1964) reported that sheep could lose up to 3 l day^{-1} in respiratory evaporation and that the sweat losses were only 1/10 of the total evaporative losses at high temperatures. Sweating rates can only be determined indirectly and are dependent on the wool length. Brook & Short (1960) reported that sweating rates from shorn sheep varied from 10 to 32 g m^{-2} hr^{-1}, whereas Knapp & Robinson (1954) estimated rates of 50 to 95 g m^{-2} hr^{-1}. The rates would be lower for sheep with fleeces.

The heat loss, as distinct from the water loss, is difficult to calculate since not all of the heat is absorbed from the body during sweat evaporation, and the reaction of water with the fleece is exothermic (Klemm, 1962), further complicating the calculation of heat loss from the body.

The sweating process has been ignored in this model and all evaporative cooling is assumed to take place in the respiratory tract. Even in shorn sheep this will only cause a small error in the heat and water balances since the evaporative process is similar in both cases, although the respiration rate may show a larger error. This can be accounted for when the critical respiration rates are set in the section modelling the transitions between activities. This approach is further supported by experiments showing that the restriction of sweating makes little difference to the heat tolerance of the animal (Alexander & Brook, 1960).

8.4128 *Respiratory cooling*

A sheep has a tidal volume of 200 to 250 ml (Macfarlane, 1964) and a respiration rate that can vary from 20 to 30 respirations per minute (r min^{-1}) in cool conditions, to 350 r min^{-1} in hot conditions. The volume per breath is relatively constant as the rate rises (Macfarlane, 1964). The relative humidity of the expired air is taken to be 85% (data for pigs, Smith, 1964), and the temperature a few degrees below the body temperature, i.e. approximately 38°C. The water content of saturated air at 38°C is 46 g m^{-3}, hence the water content of the expired air is 39 g m^{-3}. The water content of the inhaled air for a range of temperatures and humidities recorded at Middleback during both winter and summer, ranged from 4 to 7 g m^{-3}. It is therefore assumed that the water lost in each respiration was independent of the external conditions and was 32 to 35 g m^{-3}, or for a 250 ml tidal volume, about 0.0085 g r^{-1}. The latent heat of vapourization of water at 38°C is 640 cal g^{-1}, therefore the heat lost in evaporative cooling is 5.5 cal r^{-1}.

There is also an heat exchange in warming or cooling the inhaled air to 38°C. The density of air at 38°C is 1.135 g l^{-1} and the specific heat of dry air is 0.237 cal g^{-1} $^{o}C^{-1}$. The inhaled air also contained 0.034 g l^{-1} of water, and therefore the heat capacity of the inhaled air is,

$$(1.135 * 0.237 + 0.034 * 1.0) * 0.250$$

$$= .076 \text{ cal}^{o}C^{-1}\ r^{-1}$$

The total heat exchange at an air temperature of T_a and a respiration rate of R' r min^{-1} is,

$$R_p = (5.5 * 0.076 * [38 - T_a]) * R' \qquad \text{cal min}^{-1}$$

$$\text{(E8.47)} \qquad = (0.58 - 0.0053 * T_a) * R' \qquad \text{W.}$$

The table below shows the heat losses in respiration for a range of air temperatures.

		heat loss (W hr^{-1})					water loss g hr^{-1}
T_a	(°C)	10	20	30	40	50	
	30	16	14	13	11	10	15
resp	100	53	47	42	37	32	51
rate	250	133	118	105	93	80	128
r min^{-1}	350	186	165	147	130	112	179

8.413 *The sheep water balance model*

The water balance is calculated from the respiratory losses, the water necessary to excrete metabolic wastes and the salt intake, and from the water gained from drinking, forage consumption and metabolic water production.

The water lost during respiration was shown above to be 0.0085 g r^{-1}, or 0.51 * R' g hr^{-1}.

Water is also lost in both the urine and faeces. The urinary losses are assumed to be made up of two components. The first is the water necessary to flush the normal metabolic wastes from the body. Macfarlane et al. (1956) reported urine volumes of 0.7 l day^{-1} for sheep on low salt diets in summer, increasing to 1.3 l day^{-1} in winter. Other experiments have resulted in similar estimates and have demonstrated that the volume is reduced if the sheep is under water stress (Macfarlane et al., 1956, 1966; Macfarlane et al. 1958; Wilson, 1966b). In the model a constant value of 1.0 l day^{-1} is used.

Sheep grazing arid pastures usually have an additional water requirement imposed by the salt taken in with the diet and the drinking water. Macfarlane et al. (1966) measured urine concentrations of 1200 ± 500 mosmole l^{-1} which is equivalent to Wilson's (1968) estimate that 26 to 30 ml of water were required to excrete 1g of NaCl. A value of 30 ml per 1g of salt is used in the model.

Brown & Lynch (1972) showed that the water content of faeces was 61 to 66% in sheep with limited water and 70 to 76% with no restriction. The volume of faeces could be calculated from the forage intake and its digestibility, but it is always about 500 g day^{-1} dry weight. This means that 1.5 to 2.0 l day^{-1}

of water are lost in the faeces.

Macfarlane *et al.* (1966) estimated that 0.3 l day^{-1} of metabolic water was produced by sheep on normal diets. Brown & Lynch (1972) used the equation,

(E8.48) metabolic water = 0.123 * K ... ml

(E8.49) and metabolic energy, K = 59 * $W^{0.73}$ ... kcal hr^{-1}

where, W is the weight of the sheep in kg. This would be a useful relationship if a more detailed sheep energy budget is included in the model.

The water intake with the food varies with the forage type and condition. Arid zone pastures vary from 25 to 50% water by weight, and since the intake is about 1.0 kg day^{-1} dry weight, the water intake is 0.3 to 1.0 l day^{-1}. In the model the salt intake and the forage water intake are calculated in the forage intake submodel.

Most stock water in the arid zone has a significant salt content. If the salt content is C g l^{-1}, every 1.0 l of water drunk is equivalent to only (1.0 - 0.03*C) l of pure water. Wilson & Hindley (1968) found that sheep would normally take no more than 5.0 l in a single drink. This value is a maximum, and a mean drink size of about 3.0 l is used in the submodel and is reduced by the equation above if the water was saline.

The change in water balance in a unit time (one hour) is therefore,

water = drinking + food water + metabolic water - respiratory losses - salt load - urine - faecal water

$$= W_d + W_f + 0.3/24 - 0.51*R' - 0.03*S - 1.0/24 - 1.5/24$$

$$\text{(E8.50)} \qquad = W_d + W_f - 0.51 * R' - 0.03 * S - 0.09 \qquad \ldots\ l$$

where, W_d is the water drunk (l), W_f is the water in the food (l), R is the respiration rate (r min^{-1}) and S is the salt intake (g).

8.414 *The evaluation of the equations*

All the equations of the heat and water balance are listed in table 8.1. The program proceeds by evaluating any terms and part of terms, which are constant for a given day, and then those constant for a particular hour. The first step in the solution is to solve the equations for the wool surface temperature, T_s. This involves solving a polynomial including T_s to the 1st and 4th powers. It was realised that, over the temperature range 15 to 90°C, the linear approximation

$$\text{(E8.51)} \qquad \sigma * \underset{^{o}K}{T'^{4}} = 255. + 7.5 * \underset{^{o}C}{T} \qquad \ldots\ W\ m^{-2}$$

was accurate with an error of less than ± 6%. This meant that with this substitution, equations could be re-arranged and the solution calculated as shown below.

$$\text{(E8.52)} \qquad R_l = R * L * (357 + 23.1 * T_S - 28.7 * T_a) \qquad \ldots\ W\ m^{-2}$$

(E8.53) $T_s = (k * Q - 357 + [28.7 + a] * T_a + b * T_b) / (23.1 + a + b)$ ... °C

(E8.54) $a = 25.4 * (V * R)^{0.805} / R.$

(E8.55) $b = 0.402 / W.$

(E8.56) k = appropriate constant for short wave radiation load.

(E8.57) $R' = (R * L * b * [T_s - T_b] + ME) / (0.58 - 0.0053 * T_a)$ ... r min^{-1}.

(E8.58) change in water balance = $W_d + W_f - 0.51 * R' - 0.03 * S - 0.09$ ... l.

8.415 *The heat and water stress triggers*

The heat and water stress triggers are dependent on the respiration rate and the water 'credit', as calculated in the thermal and water balance model. It is assumed that the sheep will tolerate respiration rates of up to 200 r min^{-1} before moving into the shade, and of up to 300 r min^{-1} before allowing their body temperature to rise. It is difficult to get reliable estimates of these figures from published data since it is rarely clear whether the sheep had the opportunity to seek shade, or to what degree they were affected by other stresses, such as fear of the surroundings. Sheep, resting in the sun during the grazing trials, were observed to be respiring at rates of up to 150 to 200 r min^{-1}, even though shade was available. It is possible that sheep will not maintain such high respiration rates while resting in undisturbed flocks in the paddock, without seeking nearby shade. If this is the case the effect of the model will be to overestimate the water usage by the sheep. However, the observations of penned sheep do indicate that they can maintain respiration rates of up to 200 r min^{-1} if some other stress, such as thirst or hunger, is dominating. The upper limit to the respiration rate is based on Macfarlane's (1964) observation of rates of 350 r min^{-1} in sheep under extreme stress. If the respiration rate required to achieve body thermal equilibrium rises to 300 r min^{-1} or above, then the actual rate is limited to 300 r min^{-1}, and the excess heat is stored in the body. The excess heat is assumed to be uniformly distributed throughout the body, and the specific heat of the body is taken as 0.83 (Blaxter et al., 1959a). The 'very hot' trigger is set if the body temperature rises from an initial body temperature of 40°C (Mende & Raghaven, 1964), to over 42°C, the highest body temperature commonly recorded for sheep under heat stress (e.g. Lee & Robinson, 1941; Brown, 1971).

It must be emphasised that this is only an approximate description fo the thermal factors controlling sheep behaviour. Brown 1972 (as reported in Brown & Hutchinson, 1973) found that the respiration rate of free grazing animals was very variable, although showing a tendancy to be higher during maximum heat stress, while rectal temperature was inversely related to the heat stress, being higher at night. These results would suggest that respiration rate and body temperature might not be particularly suitable indicator parameters.

The inverse relationship between rectal temperature and heat load, suggests that lags in heat conduction through the fleece may be important. The lag can be estimated by the following approximation. It is assumed that the temperature of the wool surface follows a daily, sinusoidal curve, so the damping depth, D, is (Monteith, 1973),

$$\text{(E8.59)} \qquad D = (2 * K / \omega)^{\frac{1}{2}} \qquad \ldots \text{ cm}$$

where, K is the thermal diffusivity of wool ($cm^2\ s^{-1}$), and ω is the angular frequency of the oscillation (s^{-1}). If the thermal diffusivity of air, 0.24 $cm^2\ s^{-1}$, is used as an approximation for the diffusivity of wool, then,

$$D = ([2 * 0.24] / [2 * \pi / 86400])^{\frac{1}{2}}$$

$$= 81 \text{ cm.}$$

The temperature lag in a 10 cm fleece is, therefore,

$$= (10 / 81) * (24 / 2 * \pi)$$

$$= 0.5 \text{ hours.}$$

Monteith argues that the conductivity of hair and wool is at least double that of air, and this would increase the diffusivity and reduce the lag time.

Although the above method only gives a very approximate estimate of the lag, it is clear that even for long fleeces it is very much less than an hour, and can be ignored in a model with a one hour time step.

The water status of the sheep is estimated by a simple model of body water balance. The total body water of a sheep is 600 to 700 ml kg^{-1} body weight (Macfarlane et al., 1967), and the maximum amount taken in any one drink is about 5 l (Wilson & Hindley, 1968). The model estimates the water credit of a pool of 5 l of water. The sheep will refill this pool every time it drinks, and subsequently water is removed from this pool as respiratory losses, and as urine and faecal losses. Water is added to the pool from plant water intake and metabolic water, as described in section 8.412. Whenever the water credit falls below 2.0 l the sheep are assumed to be thirsty and the thirst trigger is set. If the water credit falls below 0.0 l the sheep are assumed to be dehydrated.

The water credit as used in the model has no direct relationship to a real physiological parameter. It could be replaced by a water representing the total body water. In this case the sheep would drink until it reached a fill of about 30 l and would be dehydrated if the body water fell to 25 l, i.e. it lost about 10% of its body weight or about 16% of its body water. This approach is arithmetically equivalent to the one used.

Hecker et al. (1964) found that the rumen can act as a water store in sheep, and that the animal will not become dehydrated until this store is depleted. The mean rumen volume in sheep with unrestricted water and food was 6.4 l of which about 5 l must have been water. The model could be directly related to the rumen water store, but a more detailed approach would require a model of the physiological and neurological aspects of thirst.

Macfarlane (1964b) showed that some animals do not drink sufficient liquid to replace all their body water during the hottest part of the day, but make this up only in the cooler evening hours. This is not included in the model since there is no data to indicate whether this is so in sheep which may have to walk 5 km or more to drink. It would also have little effect since the model predicts that most drinking occurs in the cooler hours.

8.416 *A validation of the heat and water stress models*

The heat balance section of the grazing model was one of the last dealt with in my project. There was not time to test the results experimentally during summer conditions which is the season that is most critical.

The model could not be expected to predict exactly the observed variables such as fleece surface temperature or respiration rate, owing to the gross approximations made in the model. For example, the sheep is assumed to be a uniform cylinder with no end effects, no appendages and with a uniform covering of wool. The assumed orientation of the cylinder with respect to the sun and wind at times must be contradictory. The spatial variation in heat load on the wool surface and resultant variations in heat load on the body are not modelled. Nor is there a complete understanding of the physiological mechanisms used by the sheep for cooling.

Published results are difficult to interpret since most outdoor experiments do not measure or report all the variables needed for the evaluation of the model. Experiments performed in metabolic chambers or other laboratory conditions, offered more chance of providing suitable test data.

Graham _et al._ (1959) and Blaxter _et al._ (1959a, b) presented data for a series of trials to investigate the heat regulation of sheep in an experimental chamber.

This chamber was controlled so that its wall temperature was equal to the air temperature; there was no short wave radiation, and almost no air movement. Based on the heat balance model already described, a simple model of this chamber was derived as follows. Long wave radiation loss from the wool surface is,

$$\text{(E8.60)} \qquad R_l = 2 * \pi * R * L * \sigma * (T_s'^{\,4} - T_a'^{\,4}) * \varepsilon_s * \varepsilon_w, \qquad \ldots \text{ W}$$

where the emissivity of the sheep (ε_s) and the walls (ε_w) are 0.98 and 0.95 respectively. Convective heat loss from the wool surface in still air is (Holman, 1963),

$$\text{(E8.61)} \qquad h_c = 1.32 * ([T_s - T_a] / [2 * R])^{1/4} \qquad \ldots \text{ W m}^{-2}\ {}^{o}\text{C}^{-1}$$

Since $(2 * R)^{-1/4}$ varies only in the range 1.35 to 1.26 for mature merino sheep it is treated as a constant and equal to 1.30, so,

$$(E8.62) \qquad C_a = 2 * \pi * R * L * 1.72 * (T_s + T_a)^{1/4} * (T_s - T_a). \qquad \ldots W$$

The conductive loss from the wool surface is,

$$(E8.63) \qquad C_f = 2 * \pi * R * L * 0.064 * (T_s - T_b) / W.$$

The heat balance at the wool surface is therefore,

$$(E8.64) \qquad 2 * \pi * R * L * (0.93 * \sigma * [T_s'^{\,4} - T_a'^{\,4}] + 1.72 * [T_s - T_a]^{5/4} + 0.064 * [T_s - T_b] / W) = 0.0$$

and the equation can be solved by the Newton-Raphson method. (Simplification to a linear equation, as in equation 8.52, would lead to too large errors in this case).

This model was tested against several sets of data presented by Graham and Blaxter. In the first case, it was used to estimate respiratory frequency for the conditions given in figure 3 of Blaxter et al. (1959a) and figure 4 of Graham et al. (1959), and the results are shown in figure 8.10. These experiments dealt with closely shorn sheep. The wool length was 0.001m at the start of the experiment. This length would have increased by 1 to 2mm between weekly clippings, so the model was tested for a wool length of 0.002m. The model predictions of respiration rate are too high at high environmental temperatures, and too low at low temperatures, although the general shape and the position of the rapid increase in respiratory frequency, match the experimental data. The discrepancy is probably due to the omission from the model of the control the sheep exercises on its skin temperature by vasodilation and vasoconstriction. At lower environmental temperatures the sheep skin temperature fell well below body temperature and circulation was restricted, thereby reducing heat loss. The model accounts for this by reducing the respiration rate further, even to negative values. (The more complete model assumes an increased metabolic rate.) At higher temperatures the sheep would be able to increase its heat loss by increasing the blood flow through its extremities (e.g. its ears). This becomes clearer in fig. 8.11, which compares the heat losses due to convection and radiation in the model, with those estimated by Blaxter _et al_. The convective losses cross-over at about 27°C; approximately the range of vasodilation as reported by Blaxter _et al_ (1959a). The heat loss due to radiation is always higher in the model. This is probably due to the skin temperature in these closely shorn sheep actually being less than 40°C, as assumed in the model, and therefore closer to the wall temperatures. This reduces the radiative loss to less than that predicted by the model, but the differential becomes smaller as environmental temperatures near 40°C.

Blaxter _et al_. (1959b) dealt with sheep with longer fleeces, however they presented less detailed data. The model was tested by comparing its predictions with the data presented in figures 1 and 2 or their paper. Figure 1 shows the change in heat production with environmental temperature for sheep with different fleece lengths. The model was extended to assume that if a respiratory rate of less than 20 r min^{-1} is predicted, then the metabolic rate is increased so that 20 r min^{-1} can be maintained, without the loss of body temperature. As the heat load increases the metabolic heat production falls until it reaches the lowest rate reported by Graham et al. (1959) for these sheep (97W). Respiration is then increased in order to maintain the body temperature. There is relatively close agreement between the model and the experimental data, with the largest errors occurring with the shortest fleeced sheep (fig. 8.12). These errors are as predicted above. The model over estimated the heat losses and compensated by increasing the metabolic heat production.

The estimated evaporative cooling predicted by the model in the same trials was compared with the data presented in Graham et al. (1959b) figure 4. The model predicts much higher evaporative losses in longer fleeced animals, than was measured experimentally (fig. 8.13). This is probably a result of the model attributing too much cooling to respiration and not taking into account the effects of vasodilation.

Although the above comparisons do not test the actual model used in the grazing model, they do give an indication of its strength and weaknesses. The simple model used above was derived in the same way as the main heat balance model and used some of the same equations. The simple model has adequately described most of the experimental results for both very short and long fleeced animals. It is clear that a more detailed model would need to include the effects of vasodilation and vasoconstriction. A model of sheep in cold conditions would also require a more detailed relationship between heat balance, metabolic heat production and grazing intake.

The heat balance model can also be investigated further by more general comparisons. For example, the maximum respiratory cooling rate predicted by the model is 80 to 120 W, depending on the air temperature. These rates are of the same magnitude as the metabolic heat production, i.e. 95 to 130 W for 40 to 60 kg live weight sheep. At low temperatures there is heat flow from the body, through the fleece to the cooler environment. In long fleeced animals vasodilation probably occurs in the ears and other extremities so increasing the heat loss, although this is not included in the heat balance model. However in air temperatures greater than body temperature, this heat loss mechanism is no longer possible, and the sheep will usually be subjected to an added heat load through the fleece. Since a large portion of the evaporative cooling will be needed to balance the environmental heat load, the metabolic heat production must fall or else the body temperature must rise. This is confirmed by the many studies showing that at high temperatures, consumption is reduced.

It appears that the model is an adequate description of the heat balance, and will form a suitable basis for the sheep movement model. The estimated respiration rates at high heat loads will be too high, but this may be compensated for in the setting of the triggers. The model would also form a suitable basis for a more detailed metabolic energy model for sheep at low temperatures, although this is not attempted in this thesis.

8.420 *The hunger trigger*

The hunger trigger was described in section 7.43 as part of the sheep consumption model, and will not be repeated here.

That section described two hunger states, dependent on the rumen contents and set by the model, but in the present behavioural model they are treated similarly.

During the initial runs of the model I found it necessary to modify the grazing model to account for some learning about better grazing sites. The original model led to high consumptions in the first hour after a non grazing period. This consumption often occurred in a heavily grazed cell, leading to the removal of the more preferred species, and high intakes of the less preferred species even though better forage occurred in nearby cells.

The intake as calculated in section 7.43 was multiplied by a factor dependent on the forage found in the previous hour of grazing,

$$f = \min \left({}_{t}\Sigma \; [p_i * b_i] \; / \; {}_{t-1}\Sigma \; [p_i * b_i], \; 1.0 \right).$$

This factor represents the ratio of the 'quality' of the forage in the present cell to the 'quality' in the previous cell grazed to a maximum of 1.0. This factor reduces consumption whenever sheep move from good pasture to poorer pasture, but does not affect it if the opposite transition is made.

Although I have attempted to include as few parameters without a physical reality as possible, some, such as this one, prove necessary to describe the behavioural patterns shown by sheep. The inclusion of this factor prevented the biomasses of some cells falling unrealistically quickly.

8.421 *Movement while grazing*

There have been no detailed studies of the movements of grazing flocks reported. My observations in Wertigo indicated that the net rate of movement of the flock varied from stationary to about 1.0 km hr^{-1}. Most graziers claim that sheep graze into the wind, and this observation is supported by the impact on the vegetation in heavily grazed paddocks. In both the Koonamore and Middleback areas, the most frequent winds are from the south and southwest and aerial photographs show signs of heavier grazing along some southern fence lines. However wind direction is not a dominant factor in controlling the movement of grazing flocks.

The model described here, attempts to account for the above observations, but must also make some arbitrary assumptions about other factors. Long term observations of flock movement, physiological condition and external environment are badly needed. These can probably only be done via a radio-telemetry system, but although this has been attempted several times, no one has yet published detailed results for sheep using large paddocks.

In the model each subflock is assumed to be located in one particular cell for the whole time increment. At the end of each increment there is a certain probability that they will move to one of the 8 neighbouring cells. Each movement shifts the sheep 0.8 km, or 1.13 km, with a mean shift of 0.97 km. The probability of moving to a new cell is set so that the average speed of a grazing flock is 0.7 km hr^{-1} in poor forage and 0.4 km hr^{-1} in good forage. Good forage is defined as situations where the sheep are eating at more than 50% of the maximum rate. This means that nearly satiated sheep will also tend to move more while seeking forage, while hungry sheep show a greater tendancy to remain in one locality and eat.

Once it has been determined that the sheep will move, the direction of movement is dependent on the wind direction and speed. The 8 neighbouring cells are regarded as 8 compass points and the wind is assumed to be blowing from one of these points. The highest probability of movement is into the direction of the wind, with a decreasing probability at greater angles to the wind. The wind speed is assumed to be calm, moderate or strong, and the probability of moving into the wind is higher with stronger winds. In calm conditions there is a similar series of directional probabilities, but this time the highest probability of movement is in the direction of the previous movement. The probabilities are shown in table 8.5.

The sheep observed in Wertigo tended to remain in flocks larger than the basic 8 to 20, especially in cooler weather. In the model it is assumed that subflocks in the same cell are in the same flock, or are at least in contact with each other. There is a probability (p = 0.7) that, if one group moves to a new cell, then other subflocks originally sharing the same cell as the first group, will follow it. This mechanism tends to hold subflocks together once they have congregated at the water-point, shelter or camp sites, but allows them to split up during the course of a day. No attempt is made to vary this contagation parameter to account for differences in behaviour in different seasons, and the model will tend to produce smaller flocks in winter since subflocks will meet at or near water, less frequently. This differs from the observations of Dudzinski & Arnold (1967, 1969), although it must be recognised that the subflock of the model, is probably more nearly equivalent to the 'flock' as defined in their study.

8.43 *Travelling behaviour*

The model assumes that sheep travel directly to their destination during any form of travelling behaviour, and does not allow for 'directed grazing' activities as discussed in section 8.400. A moving subflock is assumed to take a course through the centre of a series of cells, and this course is chosen to minimize the number of cells passed through. The speed of the subflock can be varied by altering the number of cells the sheep are assumed to pass through per hour. It is set to 2 cells per hour in this version of the grazing model, giving the sheep a mean travelling speed of 1.9 km hr^{-1}.

8.44 *The nightfall trigger*

The times of dawn and sunset are calculated as part of the heat balance models. The sheep are assumed to stop grazing in the hour after sunset, and to move to the nearest camp site. They remain in camp until the hour of dawn the next morning (Squires, 1971). During this time, the model does not calculate the hourly heat and water balance of the sheep. Instead the water loss is calculated from the mean respiration rate in the hour of reaching camp and in the hour of dawn.

No other activity is allowed once the sheep have reached camp, however if sheep become thirsty on the way to the camp site, or if they pass the water-point, they may drink.

8.45 *Application of the model to Wertigo*

So far, I have described the climatic and animal variables that must be included in the movement and behaviour model. These do not tend to change for a given locality or type of enterprise. This section describes the information needed about each particular paddock.

The paddock shape is included most readily by first describing a rectangular grid of cells. The paddock, which may itself be an irregular shape fits within the grid. This allows the simple operation of the movement model.

If the model calculates sheep positions in cells outside the paddock grid, the sheep are placed in the nearest inside cell. The structure appropriate to Wertigo, and the system of numbering the cells are shown in figure 8.5. Wertigo is represented by 37 cells, each of 64 ha, giving a total area of 2368 ha, compared with the true area of 2280 ha.

The position of the cell containing the water-point, must also be given. The present version of the model allows for only one water-point to be in use at a time, but it could be modified to select between more than one water-point, by inserting coding at the "move to water" stage of the program.

The cells containing shade and/or camp sites must also be described. This is best done by constructing arrays showing the nearest shade, or a camp site, to each of the cells (this, of course, may be the cell itself). The shade sites can be determined with the aid of aerial photographs, although some ground survey is needed to determine if certain isolated clumps of trees are actually used for shade. Camp sites must be determined by ground survey, backed up with sheep observation. This version of the model assumes that sheep move to the nearest suitable shade or camp cell, and if two cells are equally near, then to the cell nearest the water-point. However, the array can be modified to suit the topography, vegetation or other factors, as the paddock and flock behaviour become better known. The shade and camp sites used for the Wertigo model are shown in figure 8.5.

A minor adaption of the model was needed for Wertigo, when it was found that the model predicted a higher usage of cell 31 than was indicated by the validation data (section 8.53). This is readily accounted for by the fencing around the dam water-point which prevents direct movement between the section of Wertigo modelled by cells 26 and 31. Therefore special code was inserted in the model to re-route these movements to cell 32.

8.50 *Validation*

Three sources of data were available for the validation of the movement submodel. The observation data from Wertigo could be subjectively compared with the movement and behaviour patterns produced by the model. Similarly, published data about drinking frequencies, drinking times, hours spent grazing and so on, could be compared with those calculated by the model. The third source was unpublished data made available by Dr R.T. Lange and M.C. Willcocks. They had recorded the accumulation of sheep dung in permanent quadrats located in Wertigo.

8.51 *Daily movement patterns*

Some of the observed and simulated daily movement patterns are shown in figures 8.3, 8.15 and 8.16. Hourly positions and activities were printed in runs of the complete model for dates matching those on which observations were carried out. No attempt was made to match the weather of a modelled day with any particular observed day except by the time of year.

A subjective comparison of the observed and modelled patterns shows them to be very similar. The model indicated that sheep watering on the trough would move out on to the tree-less plains to the south and west of the water-point. In hot weather the sheep were shown to spend most of their time in the cell to the north of the trough. Both results match the observed sheep movements in direction, time of day, and approximate extent of travel from water. The modelled patterns for the dam water-point are again similar to those observed. The model at times allowed more, and wider scatter than was observed in Wertigo (e.g. fig. 8.15), but these situations were infrequent. The sheep probably had a tendancy not to remain in an unfamiliar area, hence sheep watering on the dam, rarely rested and camped in the north-eastern corner of Wertigo. The model had no mechanism to prevent this, although other mechanisms such as the clustering of the flocks and need to drink made it uncommon.

8.52 *Daily activity patterns*

The drinking frequencies and distribution, and the grazing time and distribution throughout the day are shown in figure 8.17 for the four seasons from the first year of the standard run (see section 11.31).

There were morning and afternoon peaks in the distribution of drinking times, similar to those observed by Lynch (1967) and Squires (1971). In conditions of extreme water demand due to hot weather and a high salt diet, a third peak appears at midday (fig. 8.17). These peaks are not deliberately built into the model and I was at first surprised to find them, however they can be explained as follows. There are three major periods of water demand each day; (i) during the night when respiration and urine losses still occur but no drinking is possible, (ii) during the morning, when most grazing and therefore most salt intake occurs, and (iii) during the mid afternoon when maximum respiratory cooling occurs, often coupled with salt intake during a late afternoon grazing period. In summer the mid afternoon water demand may also be associated with very hot conditions preventing the sheep from travelling to drink. The three stress periods, along with the periods during which drinking is not possible,tend to force a regular drinking pattern. For example, in winter when the modelled sheep were drinking 0.73 times per day, a more detailed output indicated a drinking pattern for an individual subflock as shown in figure 8.18. If a sheep drank in the morning (day 0) it did not need to drink until the late afternoon or evening of the next day (day 1), but it then needed to drink on the morning of day 3. This pattern gives a drinking frequency of 0.66. The extra drinking is due to a gradual drift due to higher water demand leading to a pattern with a frequency of 1.0 day^{-1}. The very high frequency from 5 to 6 pm is an artefact of the dam water-point. In the model many sheep camp at a site in the same cell as the dam. The model allows the sheep to drink whenever they are in the same cell as the dam and are at a level of thirst less extreme than that which usually stimulates drinking activity. When the dam results are compared with the trough water-point, which has no equivalent camp site, it is clear that the evening peak on the dam is due to sheep coming in to camp (fig. 8.17).

Similar arguments can be applied to the drinking distributions in other seasons.

The grazing time distributions show a morning peak in all seasons, with a tendancy for an afternoon non-grazing period and a second, evening, peak in hotter weather. The distribution for the dam and trough water-points are almost identical. In general the modelled sheep activity commences at about dawn, with a rest period in the middle of the day and a second, evening period of activity that finishes up to several hours after sunset. This is similar to the results of Squires (1971).

The modelled sheep walked an average of 7 to 8 km day^{-1}, but this increased to an average, for the whole flock, of 11 to 12 km day^{-1} in some conditions. Individual subflocks could travel longer distances. Squires et al. (1972) showed that in an experimental grazing trial, where food and water were at the opposite ends of a long race, merino sheep would walk up to 13.7 km day^{-1} between them. His experiment gives only an approximate estimate of walking ability since the experimental sheep did not have to walk while grazing, but it shows that the upper limit of the modelled results is realistic.

8.53 *Dung distribution data*

Dr R.T. Lange & M.C. Willcocks (pers. comm.) carried out measurements of dung accumulation in 37 permanent 120 m x 2 m quadrats from June 1972 to September 1973. The accumulation was recorded at approximately monthly intervals. The sheep were originally watering at the dam, but due to water shortages over summer they had to be shifted to the trough which is fed from a permanent underground source.

Since earliest times dung has been used as a method of observing animal activity and it has been applied in experimental situations by Warren (1971) among others. It is difficult to be certain whether the dung distribution does represent the spatial distribution of the flock's activities within the paddock. It is possible that sheep defaecate at different rates during different activities, or that the rate changes during the course of the day, or even that defaecation is stimulated in certain localities within the paddock. However, none of the permanent quadrats was in, or immediately adjacent to a camp site, shade area or in any other atypical locality. Therefore the relative distribution of dung among the quadrats should be an indication of the relative sheep activity. The only exception may be the quadrat nearest the water-point. This is the site of the highest dung accumulations (20 to 25% of the total dung collected) and also shows the highest rate of change in dung accumulation with distance from the water-point. Therefore, whereas the other quadrats were probably representative of the relatively homogenous cells centred on them, the water-point quadrat may not have been.

The results of Lange & Willcocks are shown in figure 8.19 where the dung accumulation in each cell is expressed as a percentage of the total. These were compared with the time spent in 'extensive activities' in the modelled sheep movement. 'Extensive activities' included all those activities which are not confined to a small area in a fixed position. Grazing, travelling and resting are extensive activities, whereas shading, camping or drinking are not. The results of runs of one year for sheep on either the dam or the trough water-point are shown in figure 8.19.

The distributions are very similar, but with the model appearing to keep the sheep nearer to the dam than observed in Wertigo. Spearman rank correlations tests show a high correlation between the observed and modelled results ($r_s = 0.676$, $p < 0.001$ for the 'dam-accumulated' and 'dam-simulated' results of figure 8.19).

It must be pointed out that these distributions are highly variable. For example the dung collected from the quadrats on the first collection date ('dam- accumulated') shows a slightly worse correlation (r_s = 0.656) with the dung collected during the collection period ('dam-experiment') than it does with the simulated extensive activities.

The data were collected for a shorter period for the trough water-point than for the dam, and were also confined to the summer months. Hence the extensive activities distribution for the modelled sheep during the December-February period was plotted as a comparison. It is clear that the sheep show a reduced range in the summer months, and the distribution matches the observed distribution more closely. The observed trough data is complicated by some sheep which were able to water at the dam. Most of these sheep came from the western neighbouring paddock (which shares the dam water-point), and these sheep had little or no contact with the main flock and probably accounted for most of the dung in the southern end of the paddock.

8.54 *Conclusions*

In conclusion all the comparisons between observation or other real data, and the model output appear to confirm that the model is a realistic description of sheep movement and behaviour. This is true despite the many approximations and assumptions made in the model.

The model could be improved by validating the sheep heat and water balance models, and possibly by simplifying them by substituting empirical equations. The effect of learnt behaviour should also be included, and I find it surprising that the model works so well without this process. Alternatively the model could be simplified by restructuring it and reducing its many calculations. This will be necessary if multi-paddock systems are to be simulated.

For the present paddock model, the sheep movement model was adequate, although time consuming. Approximately 60% of the central processor time was used in the sheep movement model (i.e 100 msec per 160 msec of C.P. time required per day of simulation). This could be reduced by using a smaller number of subflocks since this had little effect on the results in general, except to increase the variance of the movement patterns and associated parameters.

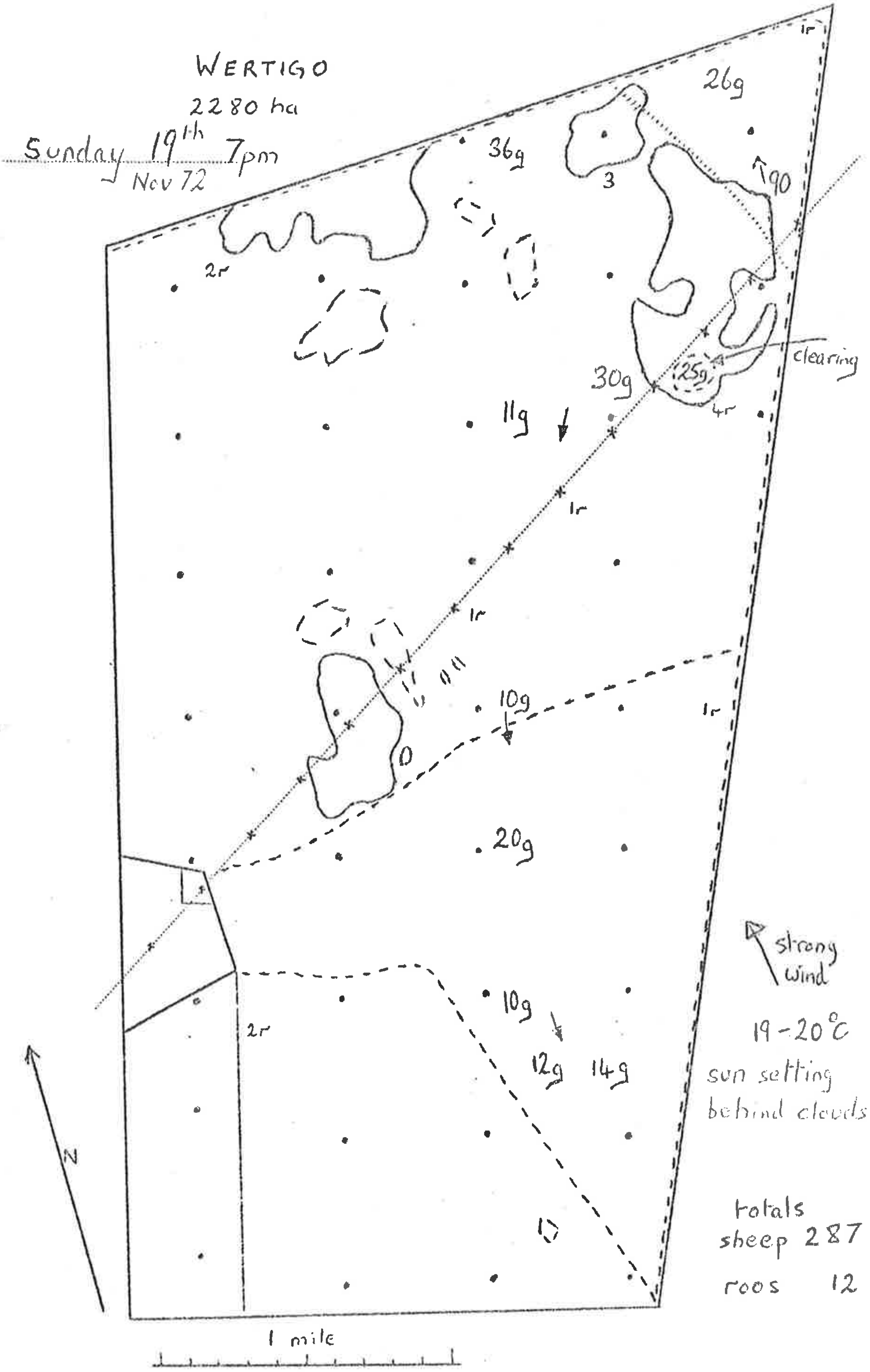


Fig. 8.1. An example of a map of sheep position and activity produced on one observation time in Wertigo. Grazing is indicated by 'g' and kangaroos by 'r'. The arrow shows the direction of movement or travelling.

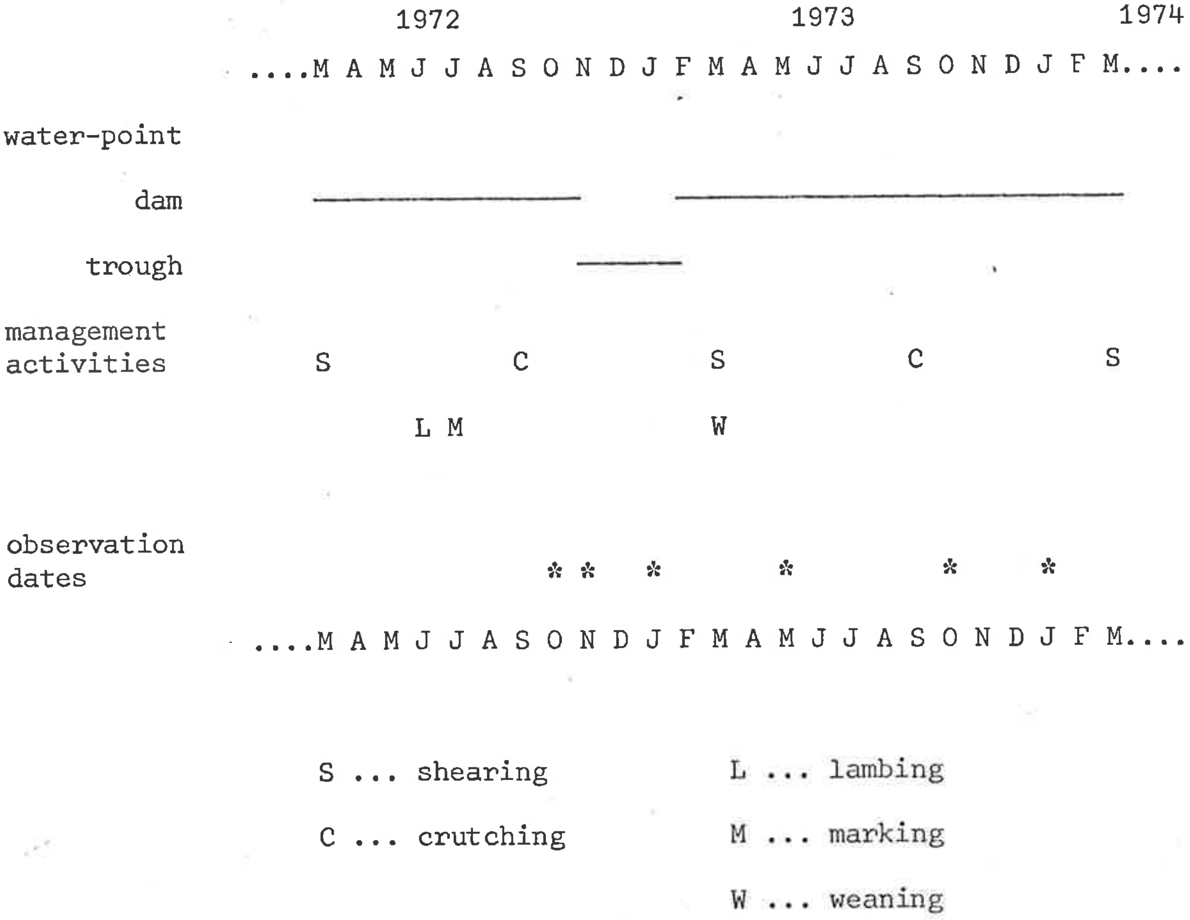


Fig. 8.2. The major management activities in Wertigo and the dates on which observations of movement and behaviour were made.

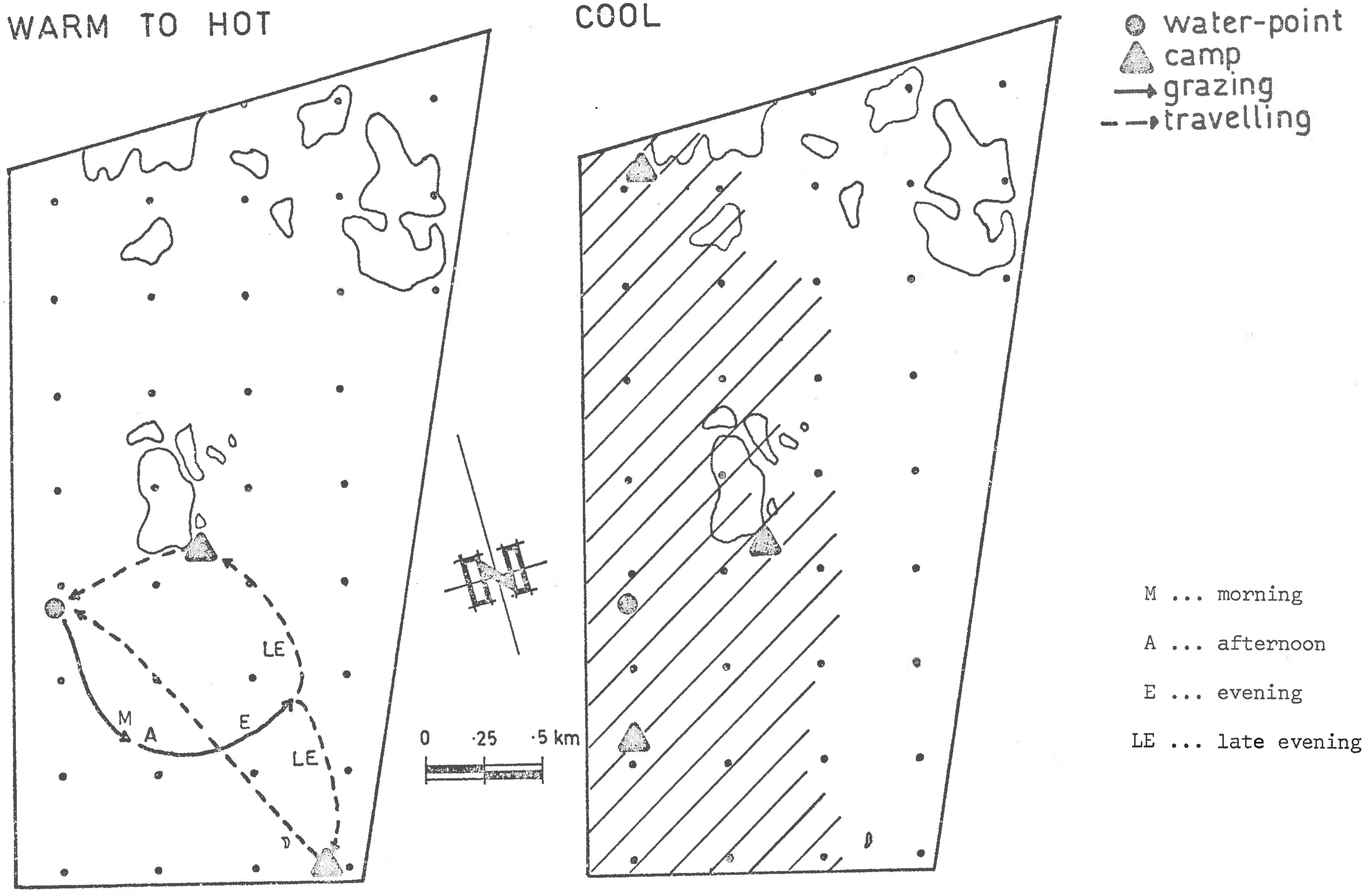


Fig. 8.3a. The sheep movement patterns as observed in Wertigo. The shaded area in the right hand map indicates that the flock was moving within this area but with no regular pattern.

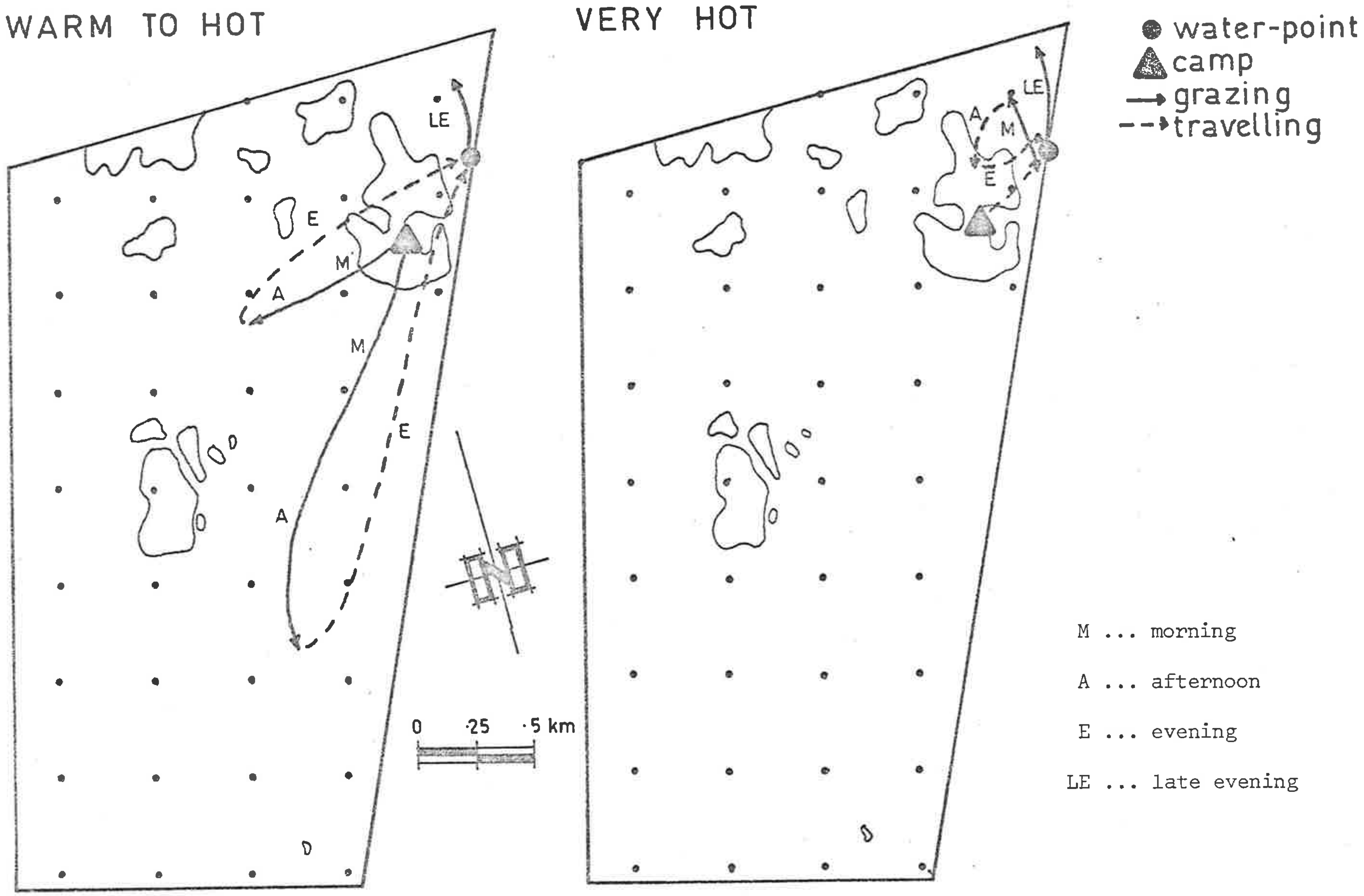


Fig. 8.3b. Sheep movement patterns as observed in Wertigo.

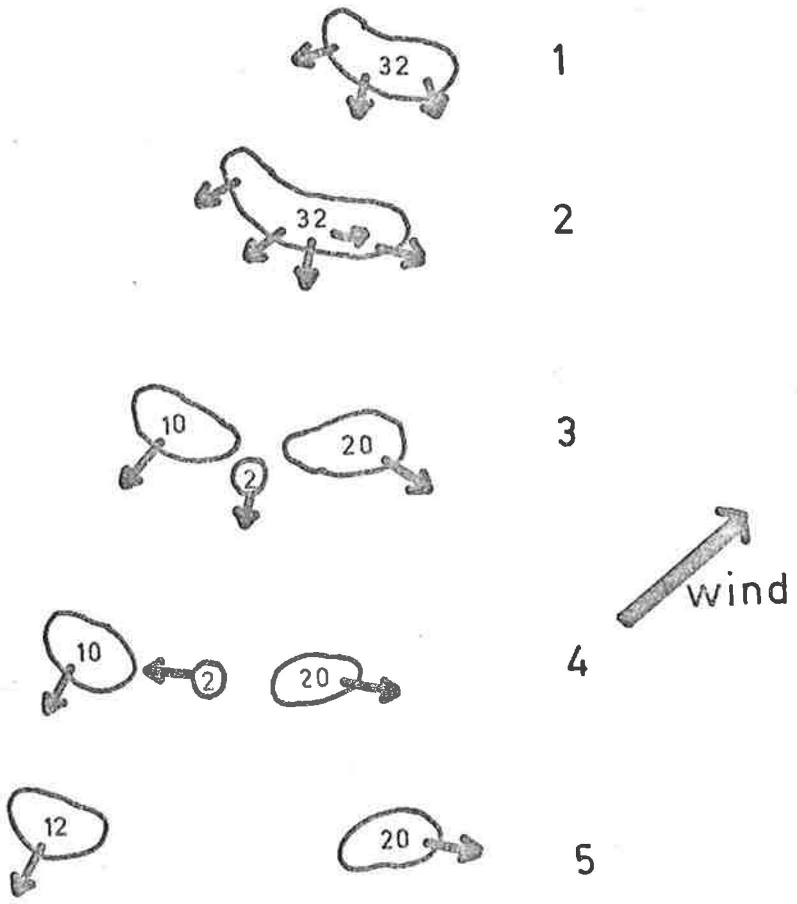


Fig. 8.4. The splitting of one flock into two or more flocks as observed on many occasions in Wertigo. The splitting seemed to be due to the combined effects of a gradual drift while grazing, combined with a tendancy to stay together.

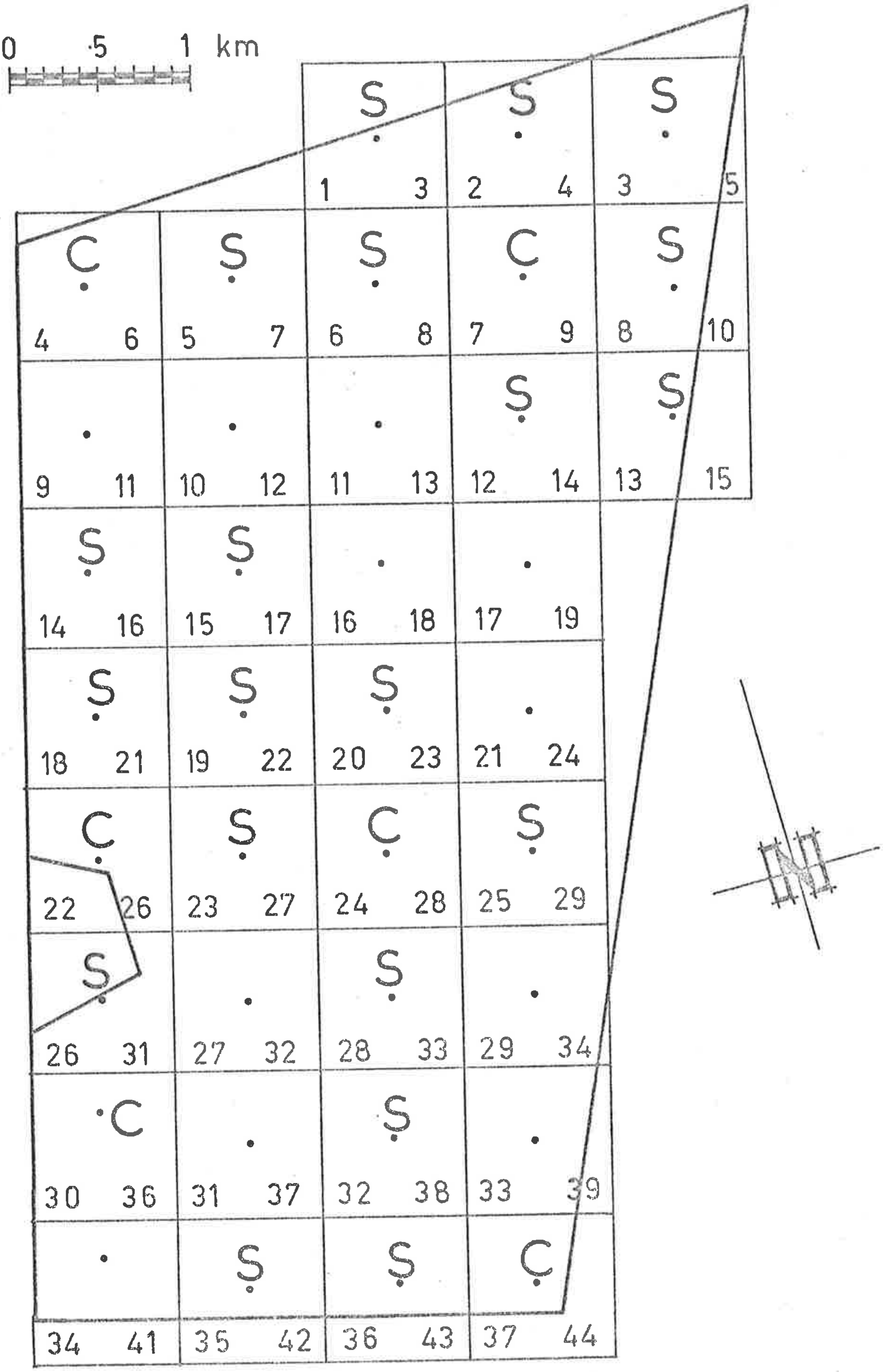


Fig. 8.5. The distribution of the cells used in the model with respect to the permanent markers in Wertigo. S indicates cells with shade, while C indicates a camp site. The numbering of the cells in the sheep behaviour section (right) and the rest of the model (left) is also shown.

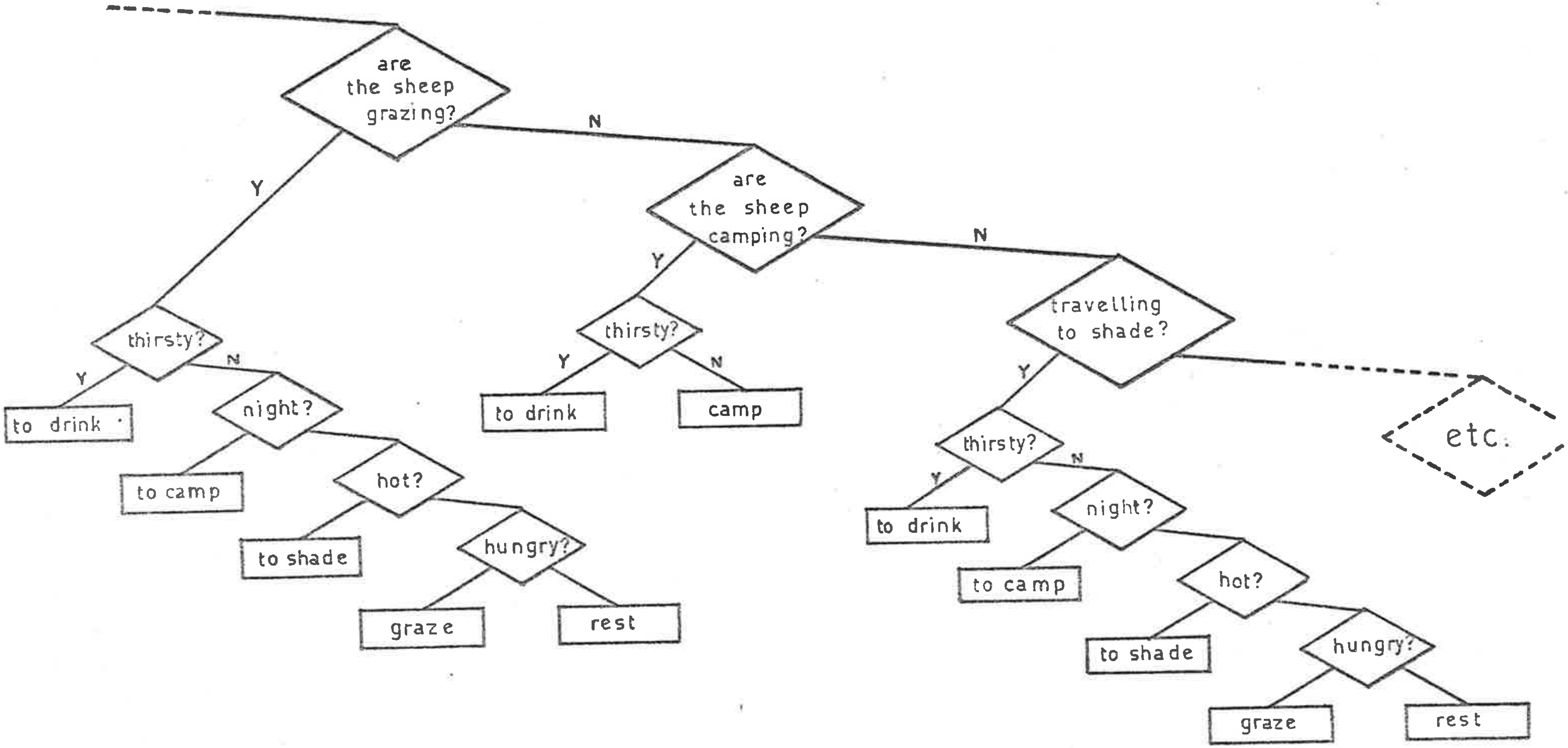


Fig. 8.6. A section of a flow chart of the decision process in the behaviour section of the model.

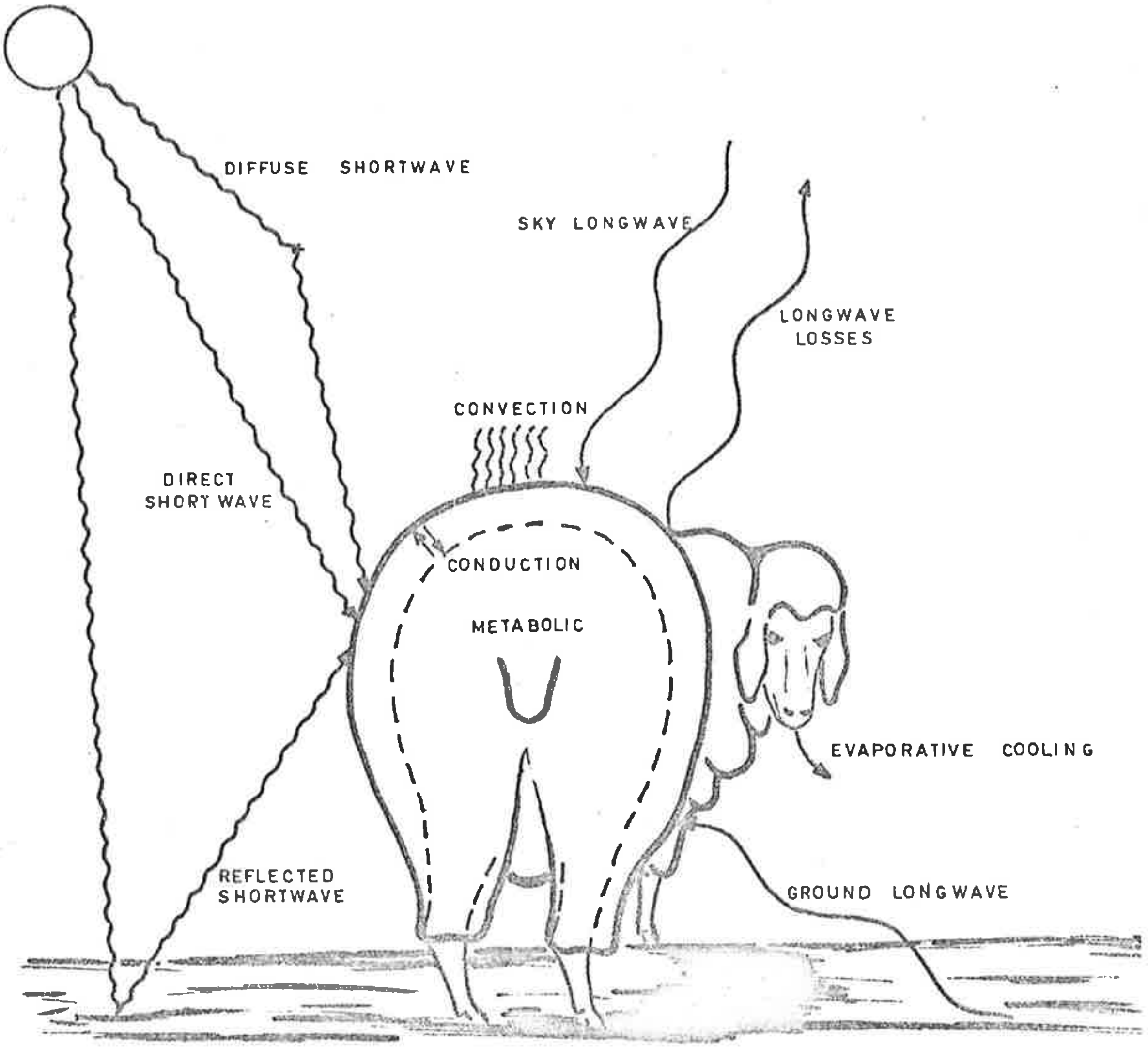


Fig. 8.7. The heat flows estimated in calculating the heat balance of a sheep.

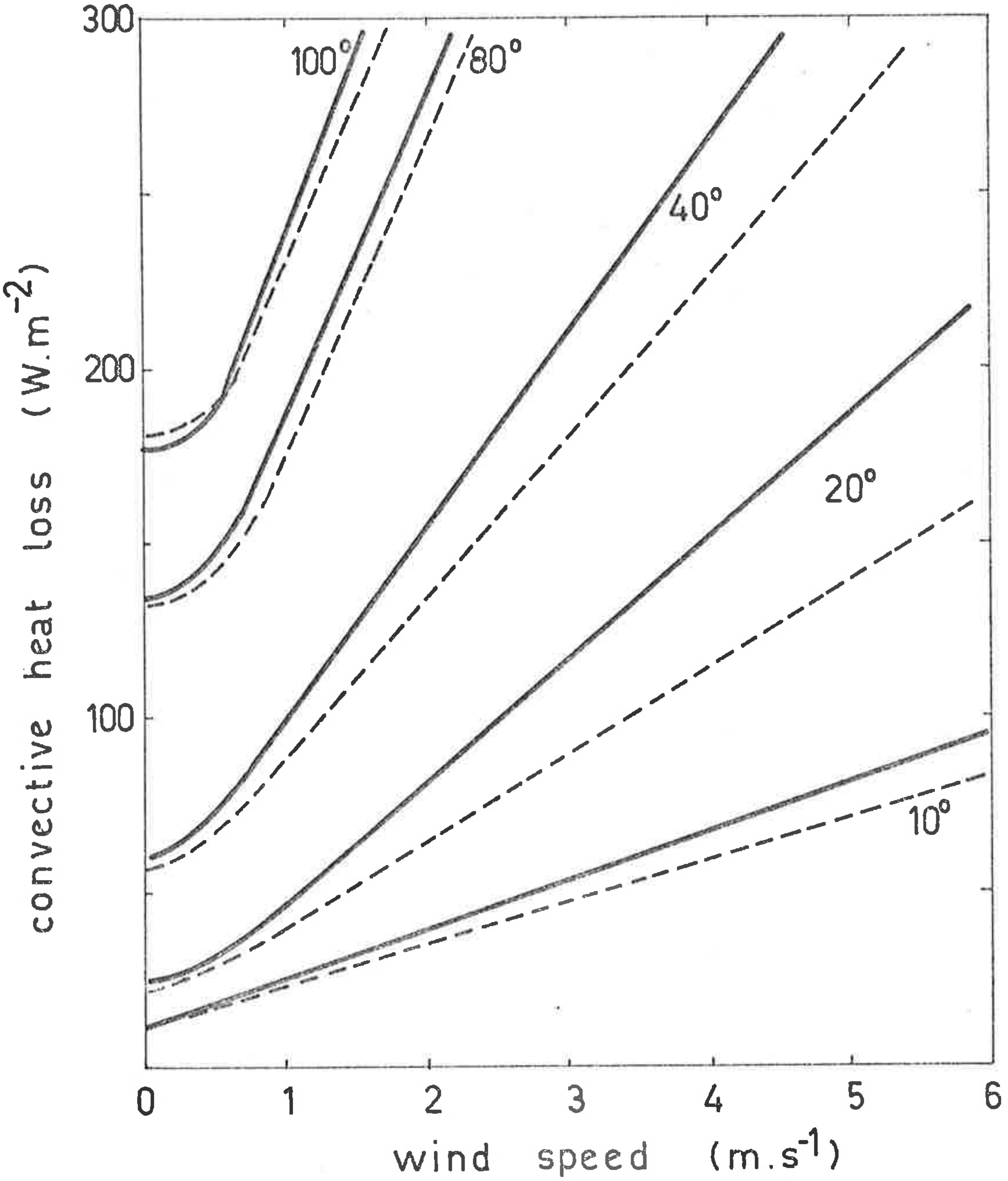


Fig. 8.8. A comparison of the convective heat loss as a function of wool-tip temperature excess (°F) and wind speed. Based on figure 1 of Priestley (1957). The solid lines are the model output and the dashed lines represent Priestley's estimates.

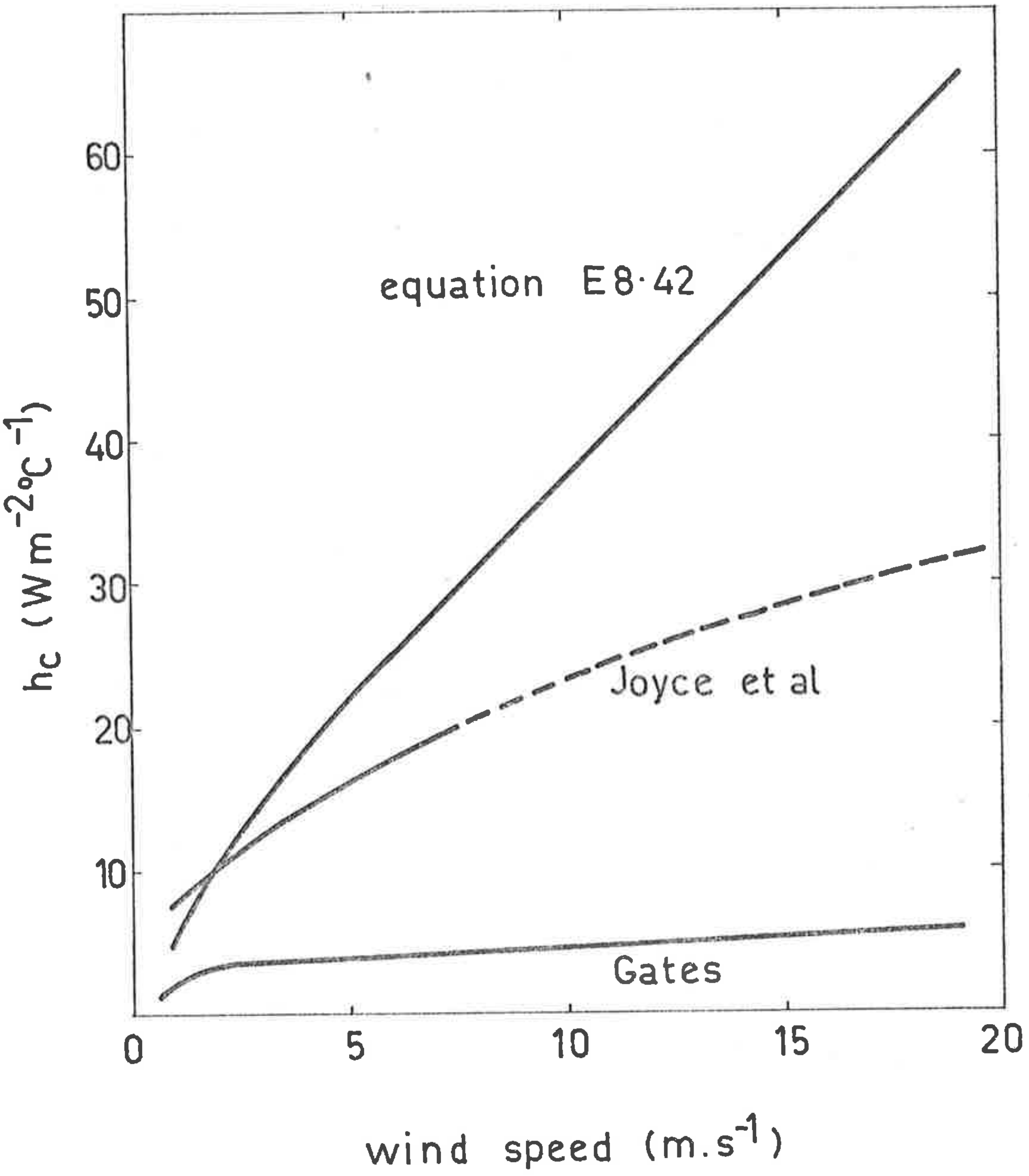


Fig. 8.9. A comparison of the three equations for estimating the convection coefficient h_c. The Joyce et al. equation is an empirical equation based on wind velocities of up to only 7 m s^{-1}.

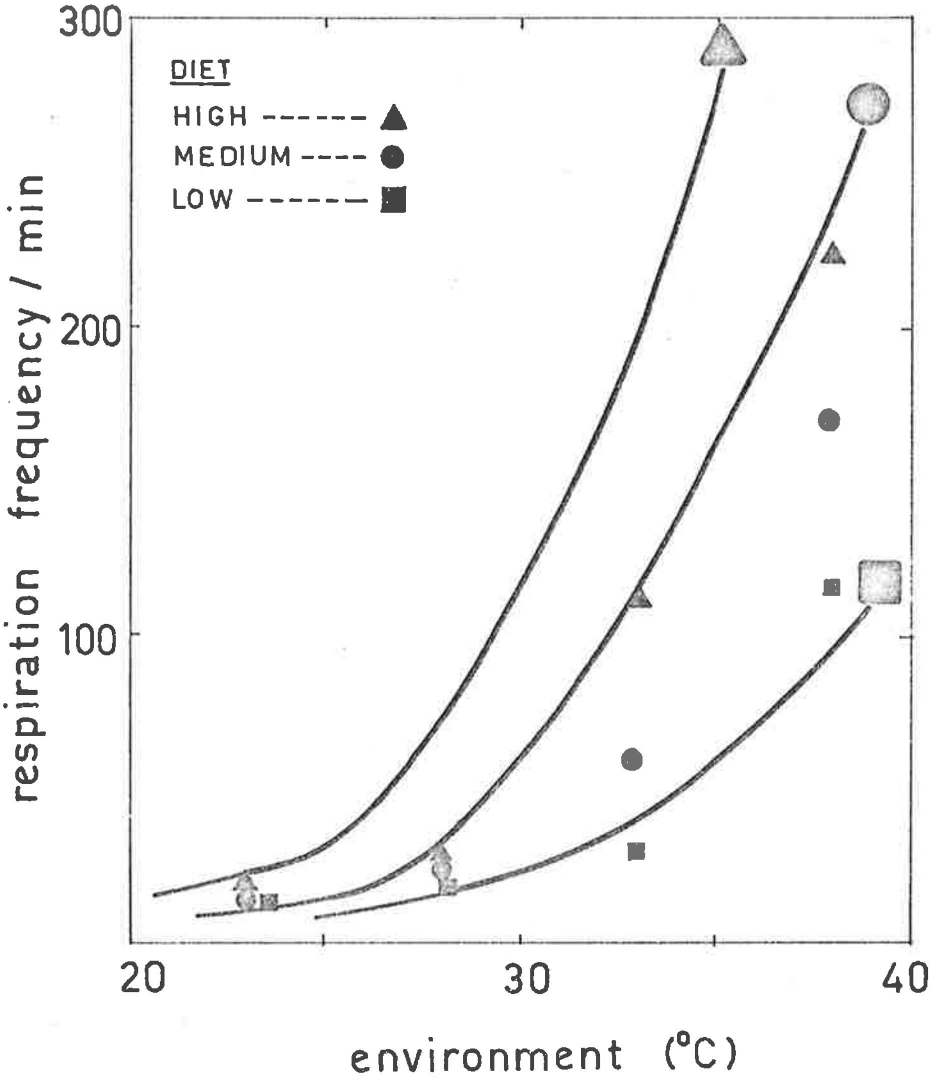


Fig. 8.10. A comparison of the model output and figure 3 of Blaxter *et al.* (1959a). The respiratory frequency of sheep 23 on different diets and at different environmental temperatures. The lines represent the model output.

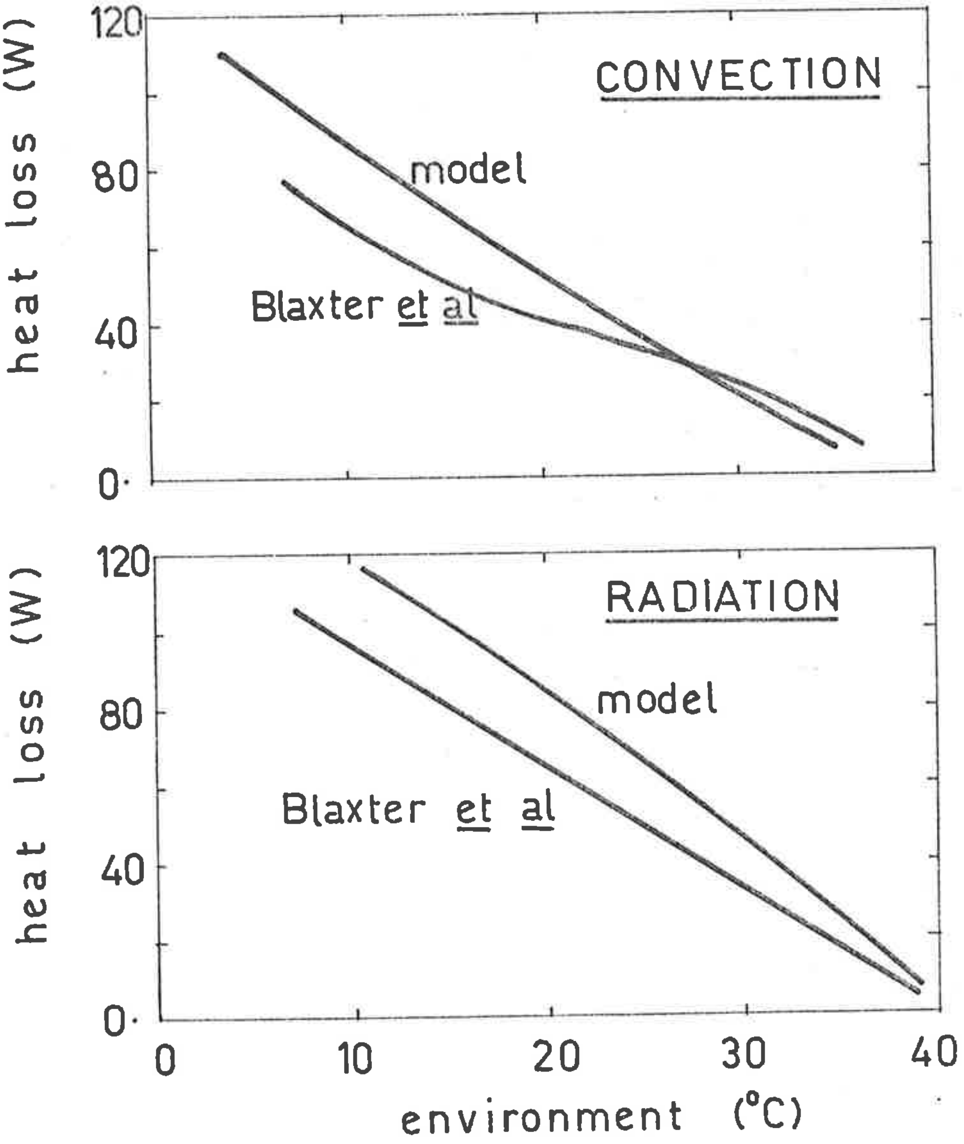


Fig. 8.11. A comparison of the heat losses due to radiation and convection as measured by Blaxter et al. (1959a, figure 7) and estimated in the model.

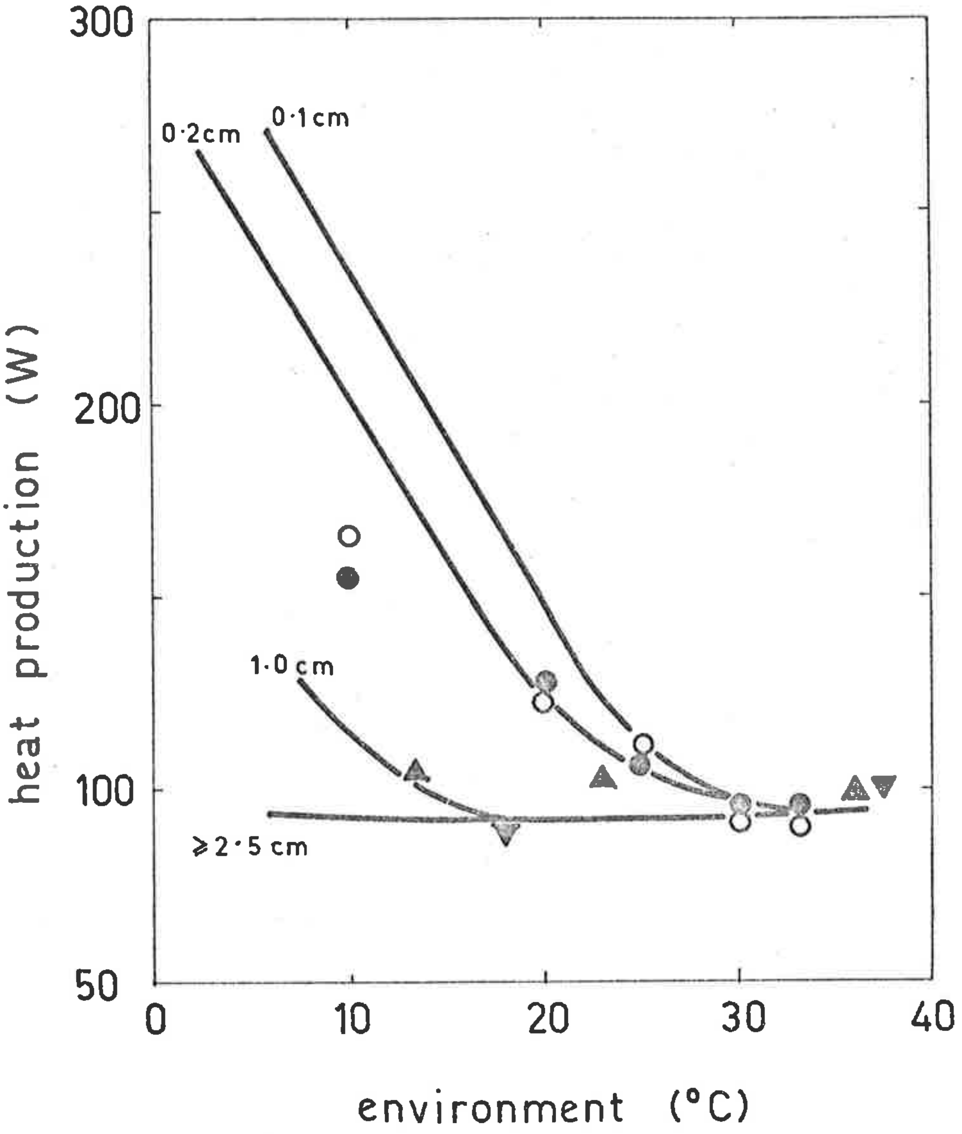


Fig. 8.12. The total heat production of sheep with different fleece lengths (●, = 0.1 cm; ▲ = 2.5 cm; ▼ = 4.5 cm) in relation to environmental temperature. The data is from Blaxter et al. (1959b, figure 1) and the lines represent the model output.

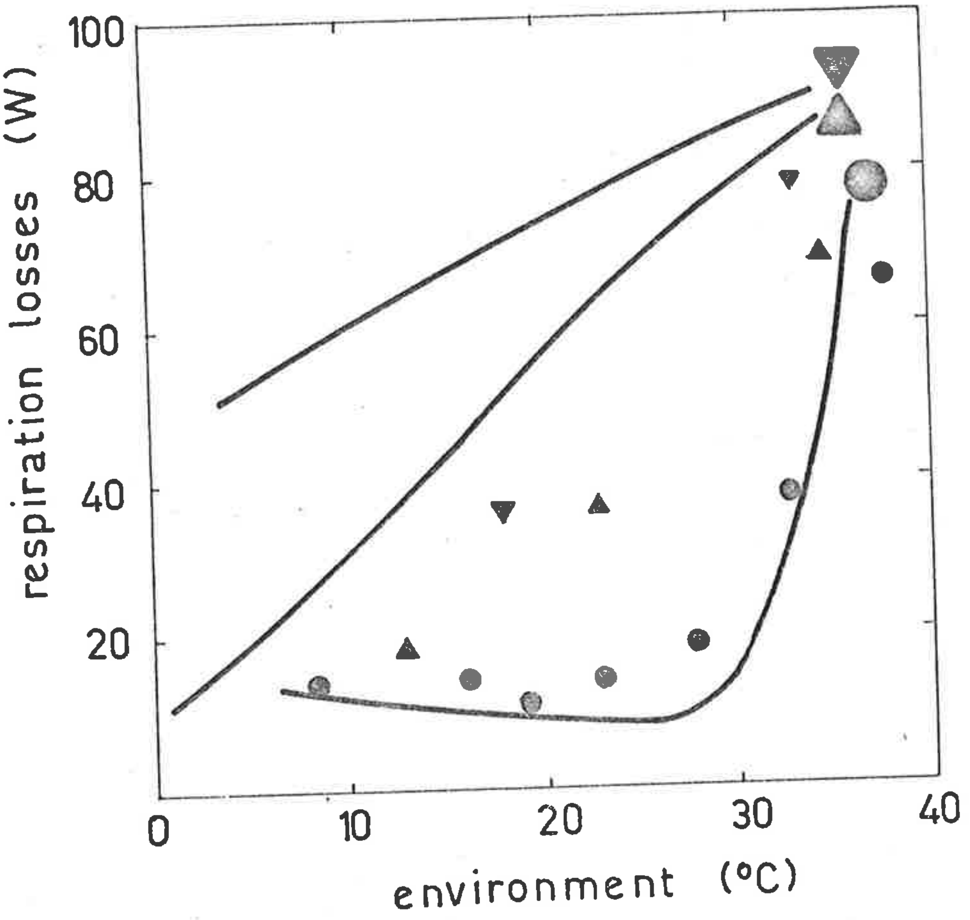
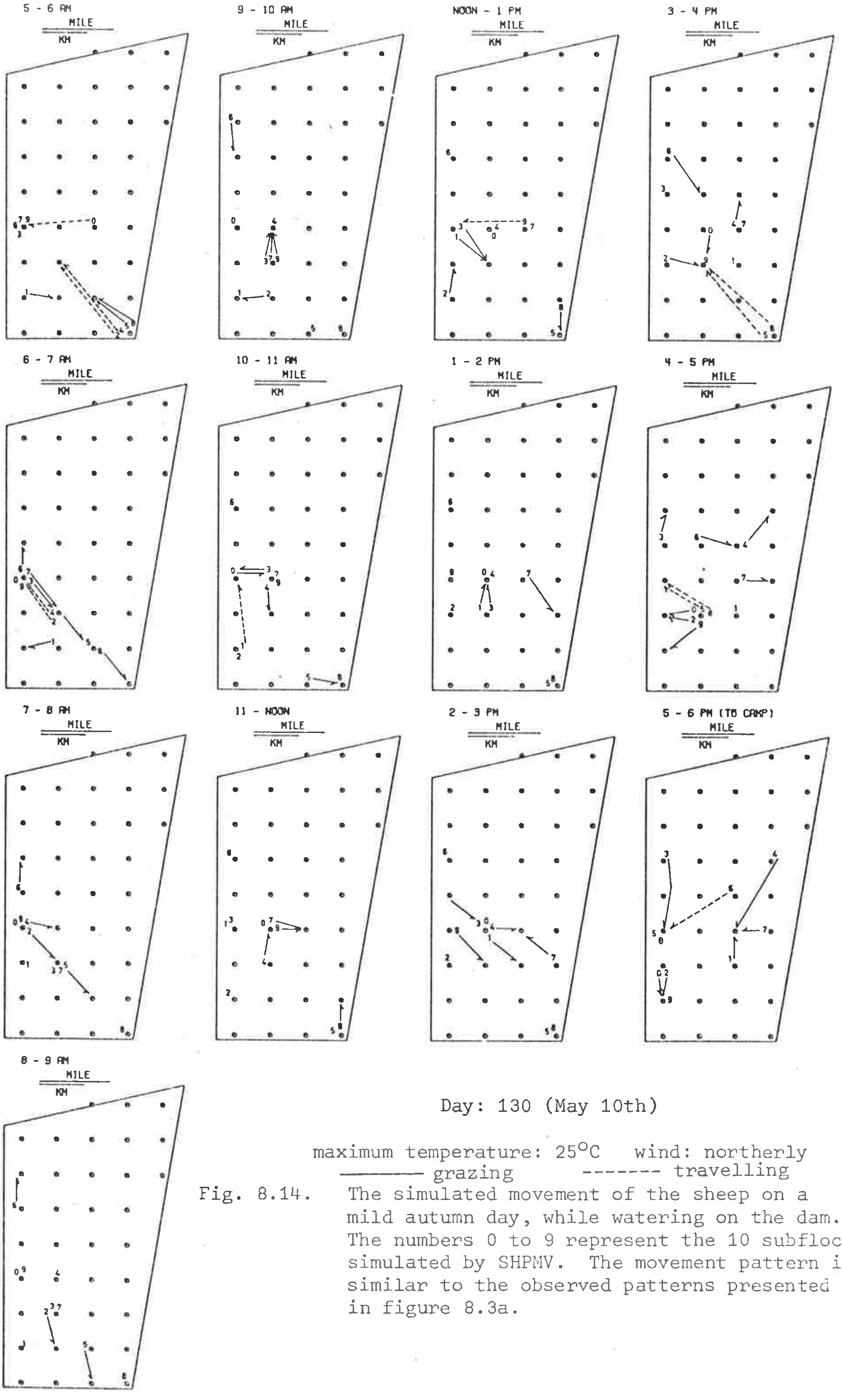


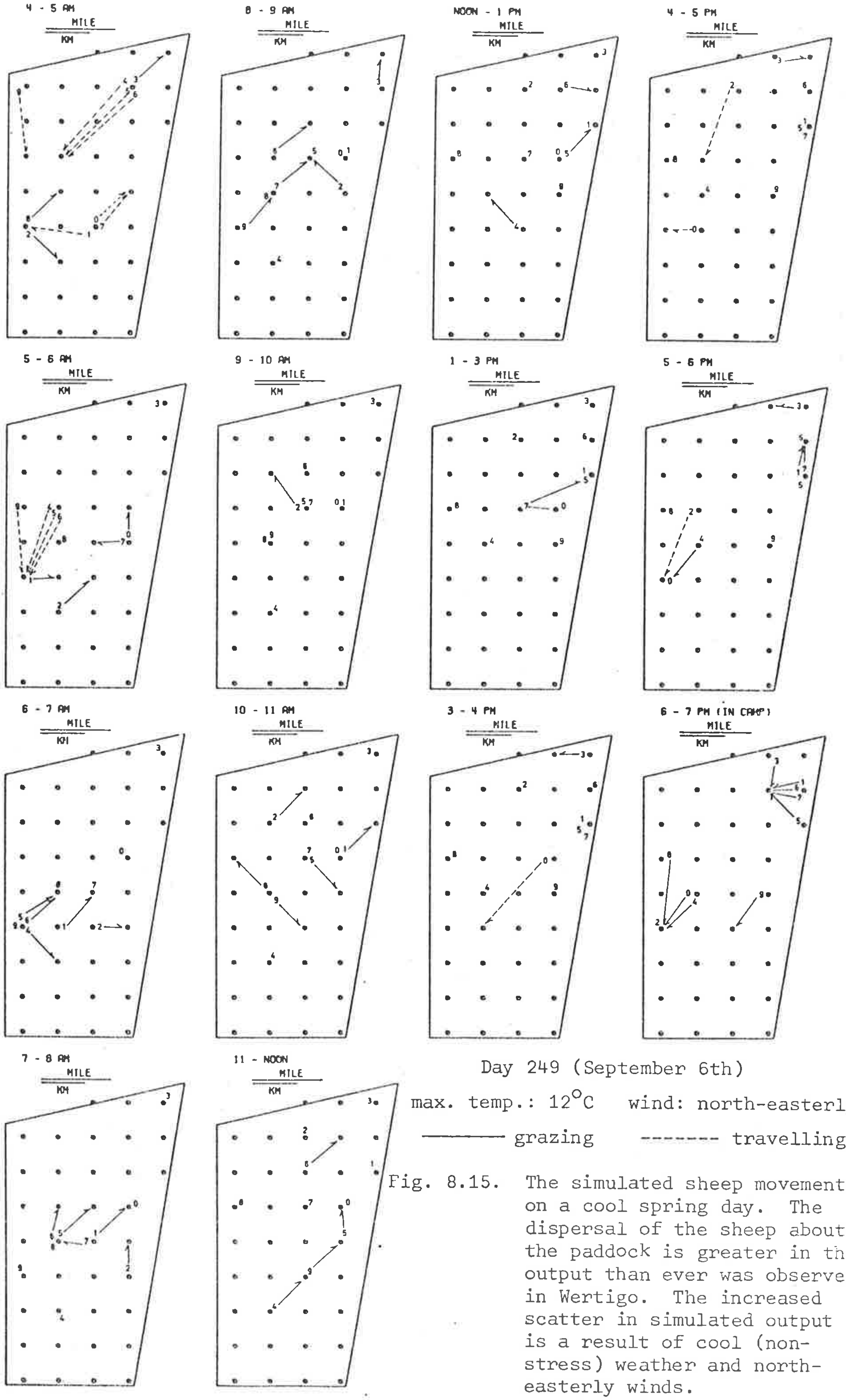
Fig. 8.13. The loss of heat by evaporation at different fleece lengths, in relation to environmental temperatures (● = 0.1 cm; ▲ = 2.5 cm; ▼ = 4.5 cm). The data is based on Blaxter *et al*. (1959b, figure 2) and the lines represent the model output.



Day: 130 (May 10th)

maximum temperature: 25°C wind: northerly
——— grazing ------- travelling

Fig. 8.14. The simulated movement of the sheep on a mild autumn day, while watering on the dam. The numbers 0 to 9 represent the 10 subflocks simulated by SHPMV. The movement pattern is similar to the observed patterns presented in figure 8.3a.

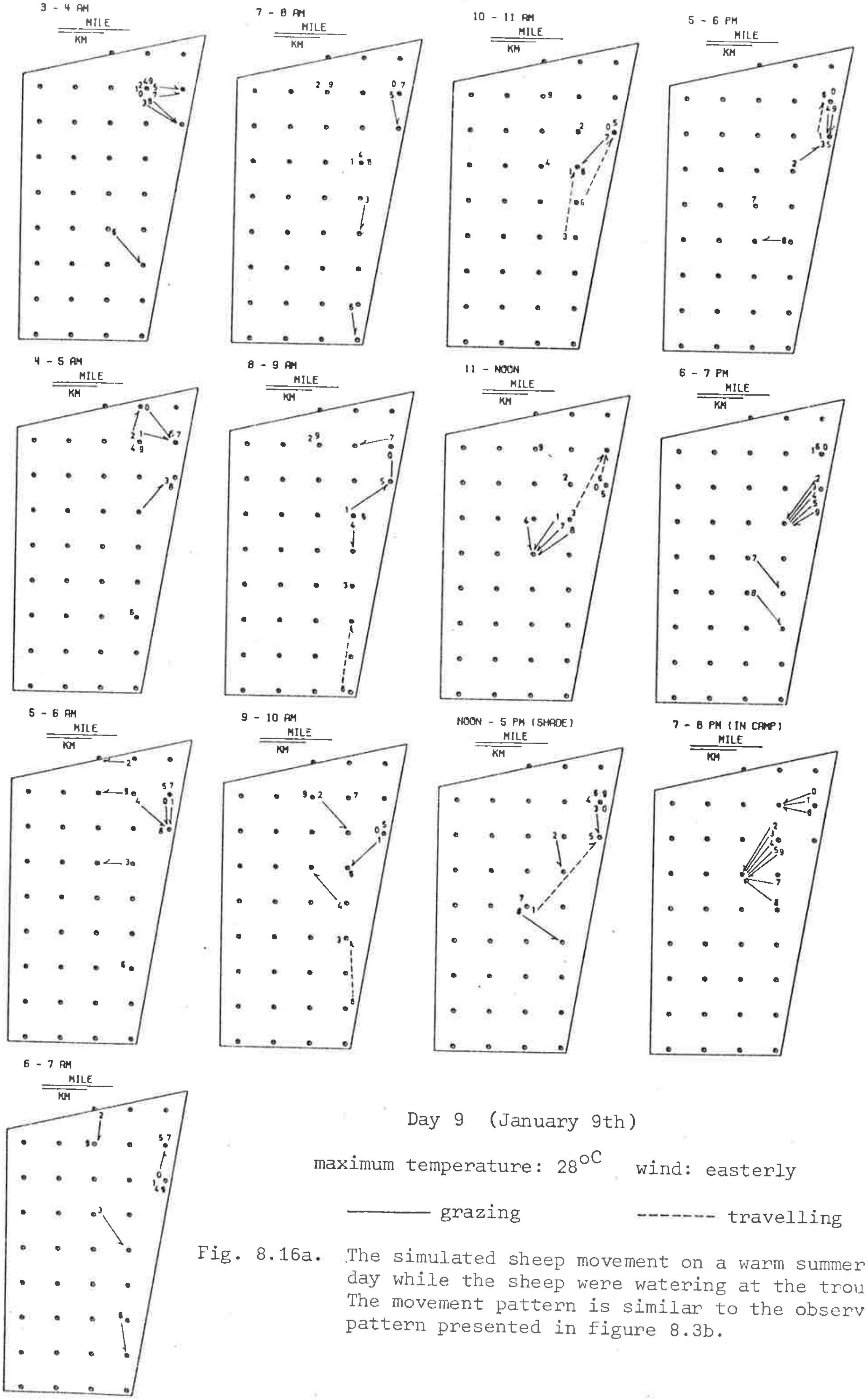


Day 249 (September 6th)

max. temp.: 12°C wind: north-easterly

——— grazing ------- travelling

Fig. 8.15. The simulated sheep movement on a cool spring day. The dispersal of the sheep about the paddock is greater in this output than ever was observed in Wertigo. The increased scatter in simulated output is a result of cool (non-stress) weather and north-easterly winds.

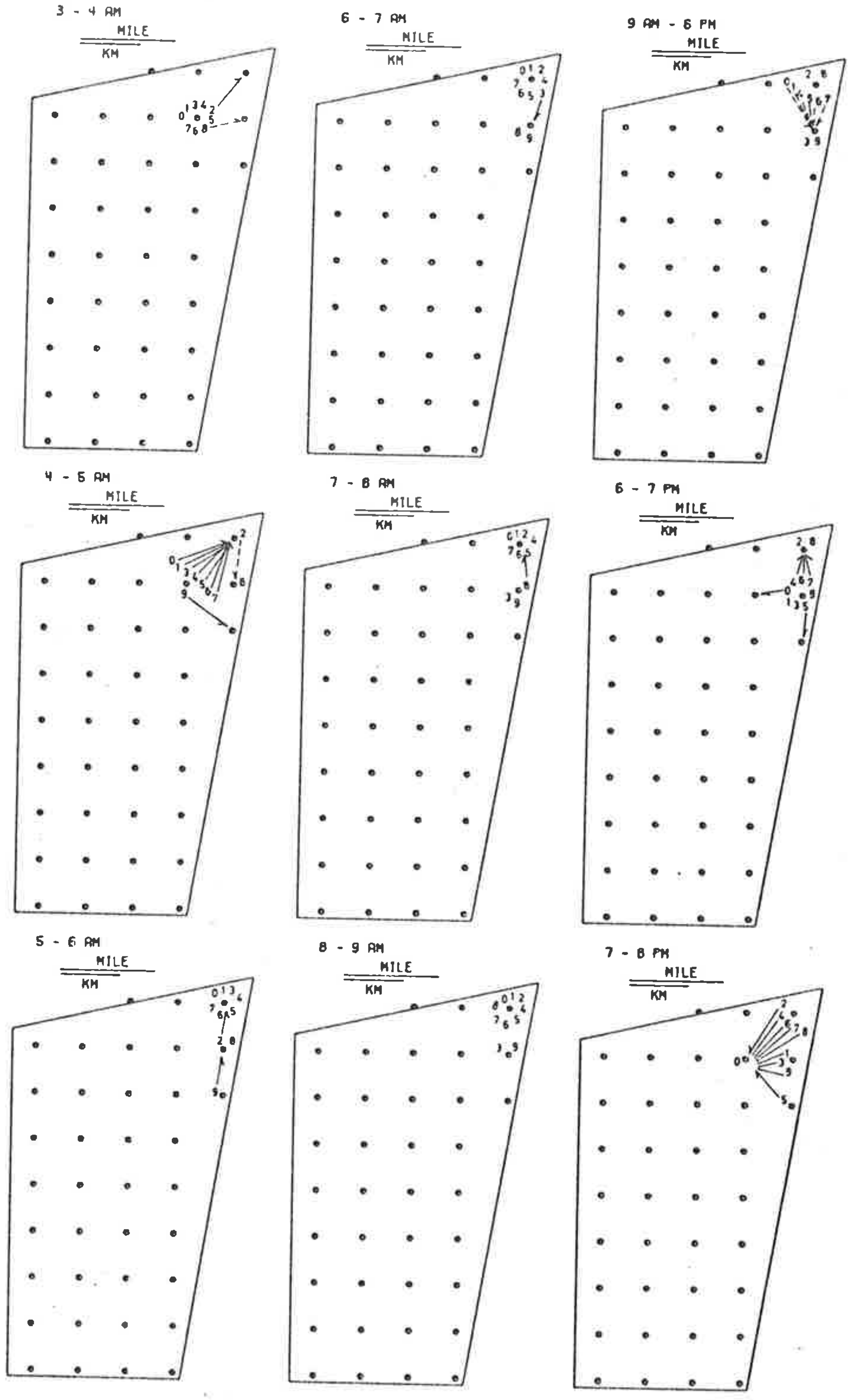


Day 9 (January 9th)

maximum temperature: $28^{o}C$ wind: easterly

——— grazing ------- travelling

Fig. 8.16a. The simulated sheep movement on a warm summer day while the sheep were watering at the trough. The movement pattern is similar to the observed pattern presented in figure 8.3b.



Day 12 (January 12th)

maximum temperature: 37°C wind: southerly

Fig. 8.16b. The simulated sheep movement on a clear, hot, summer day while the sheep were watering at the trough. The movement pattern is similar to the observed pattern presented in figure 8.3b.

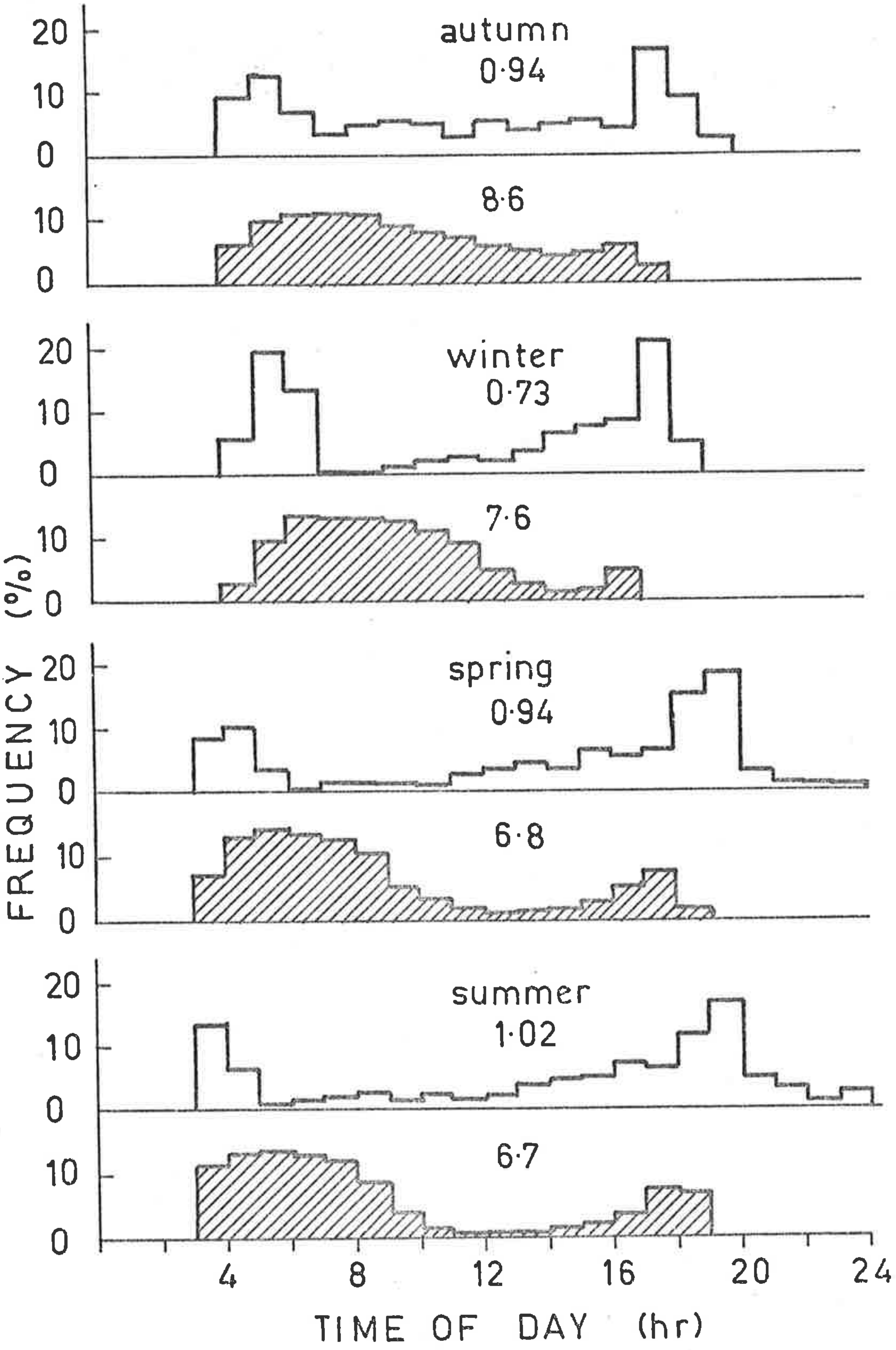


Fig. 8.17a. The distribution of drinking (open) and grazing (shaded) throughout the day while the sheep were on the dam. The numbers above each graph represent the mean drinking frequency (drinks per day) and the mean grazing time (hr day^{-1}). The vertical scale is the proportion of the total time or total number of drinks within the class interval.

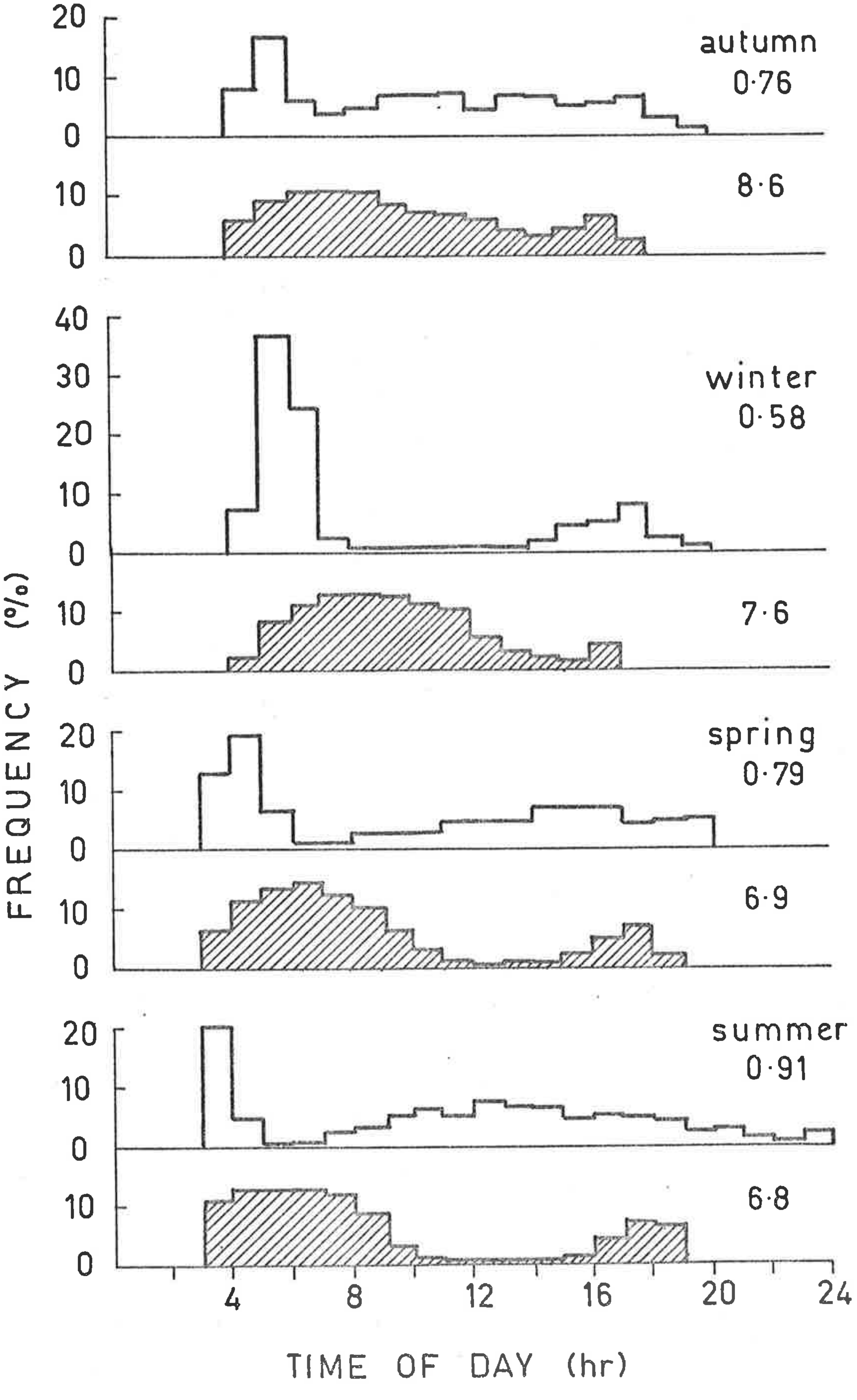


Fig. 8.17b. The distribution of drinking (open) and grazing (shaded) throughout the day while the sheep watered at the trough.

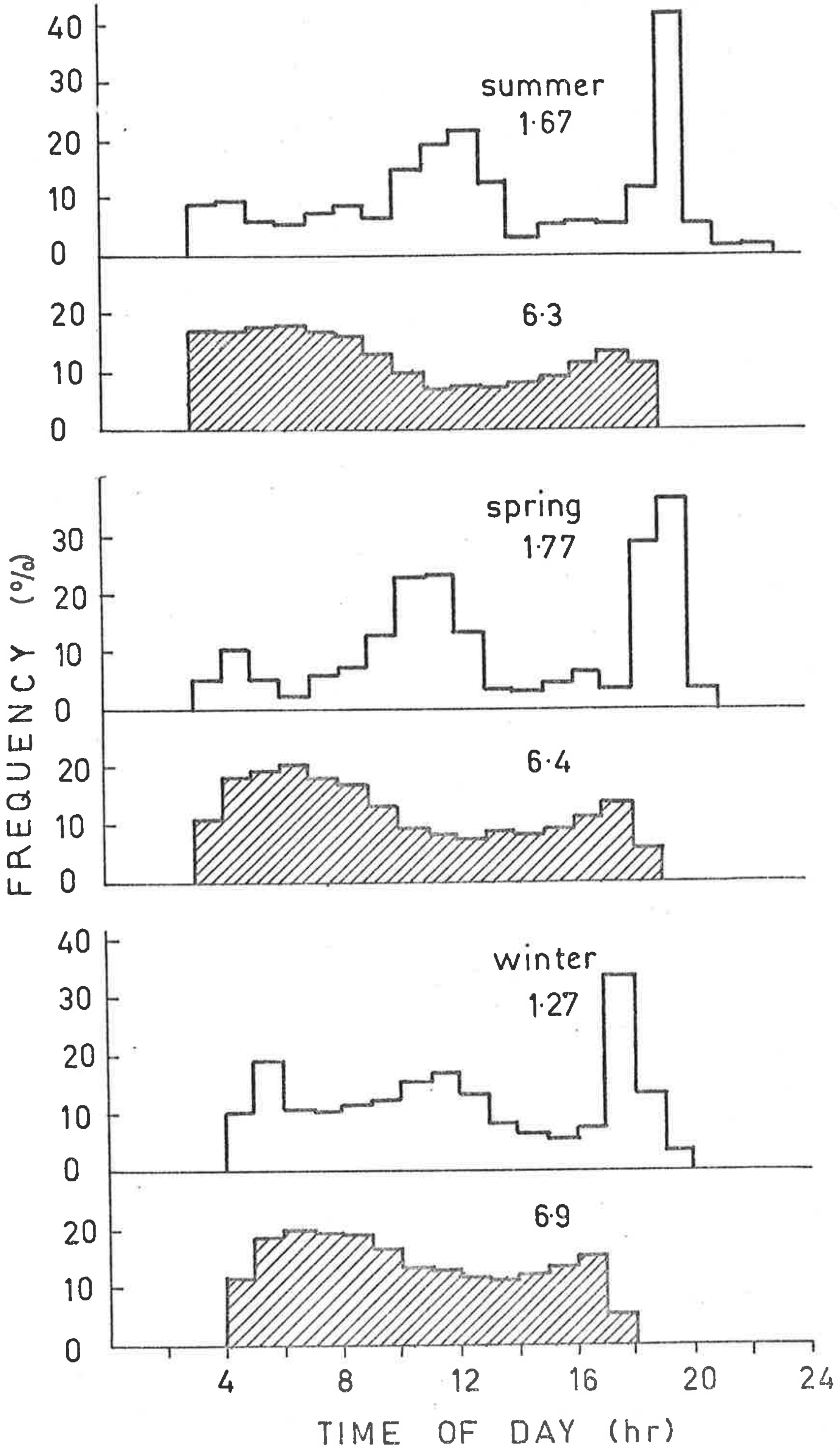


Fig. 8.17c. The distribution of drinking (open) and grazing (shaded) throughout the day during seasons of water stress.

(Note: the vertical scale is in error by a factor of X2).

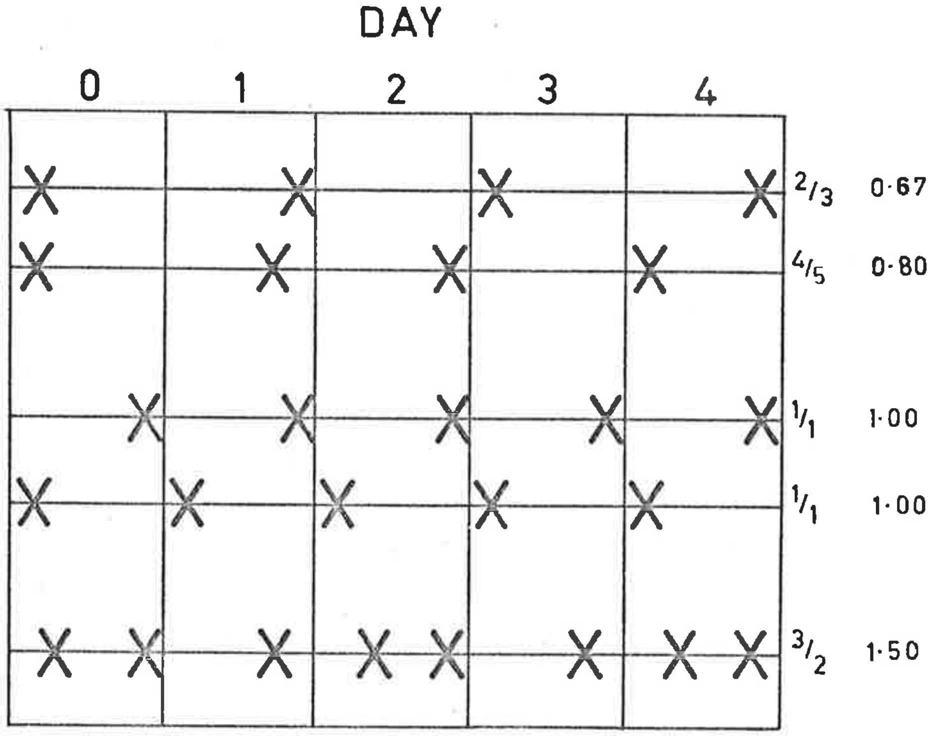


Fig. 8.18. The drinking patterns in the sheep behaviour model. The crosses represent the times of drinking over a 5 day period (morning is on the left of each vertical division and evening on the right). The numbers on the right hand side are the resultant drinking frequencies (drinks per day).

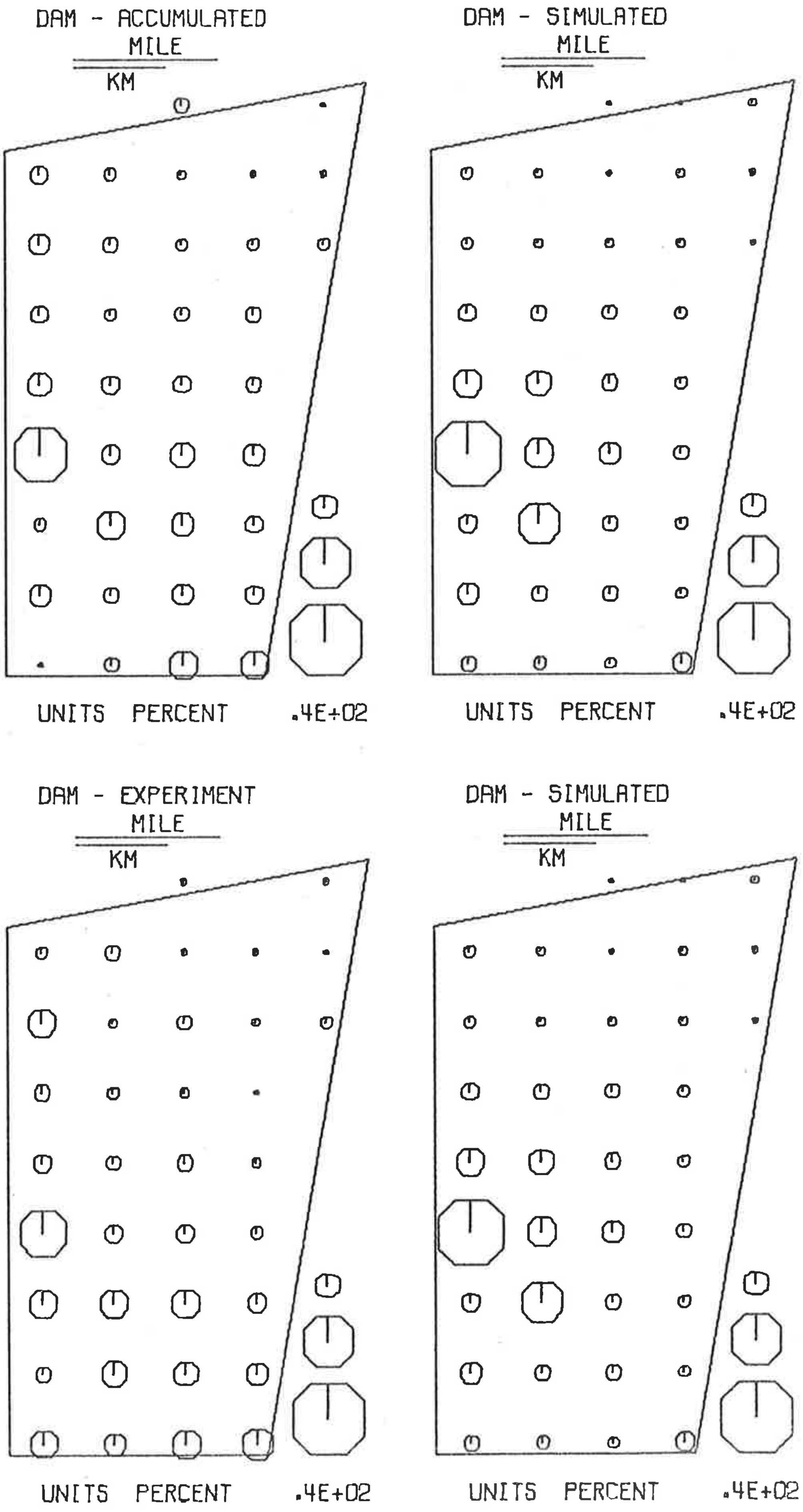


Fig. 8.19a. A comparison between the dung distribution (left hand plots) and the model output described in section 8.53. 'Accumulated' refers to the dung present at the first collection, and 'experiment' to the dung collected over the period of observations.

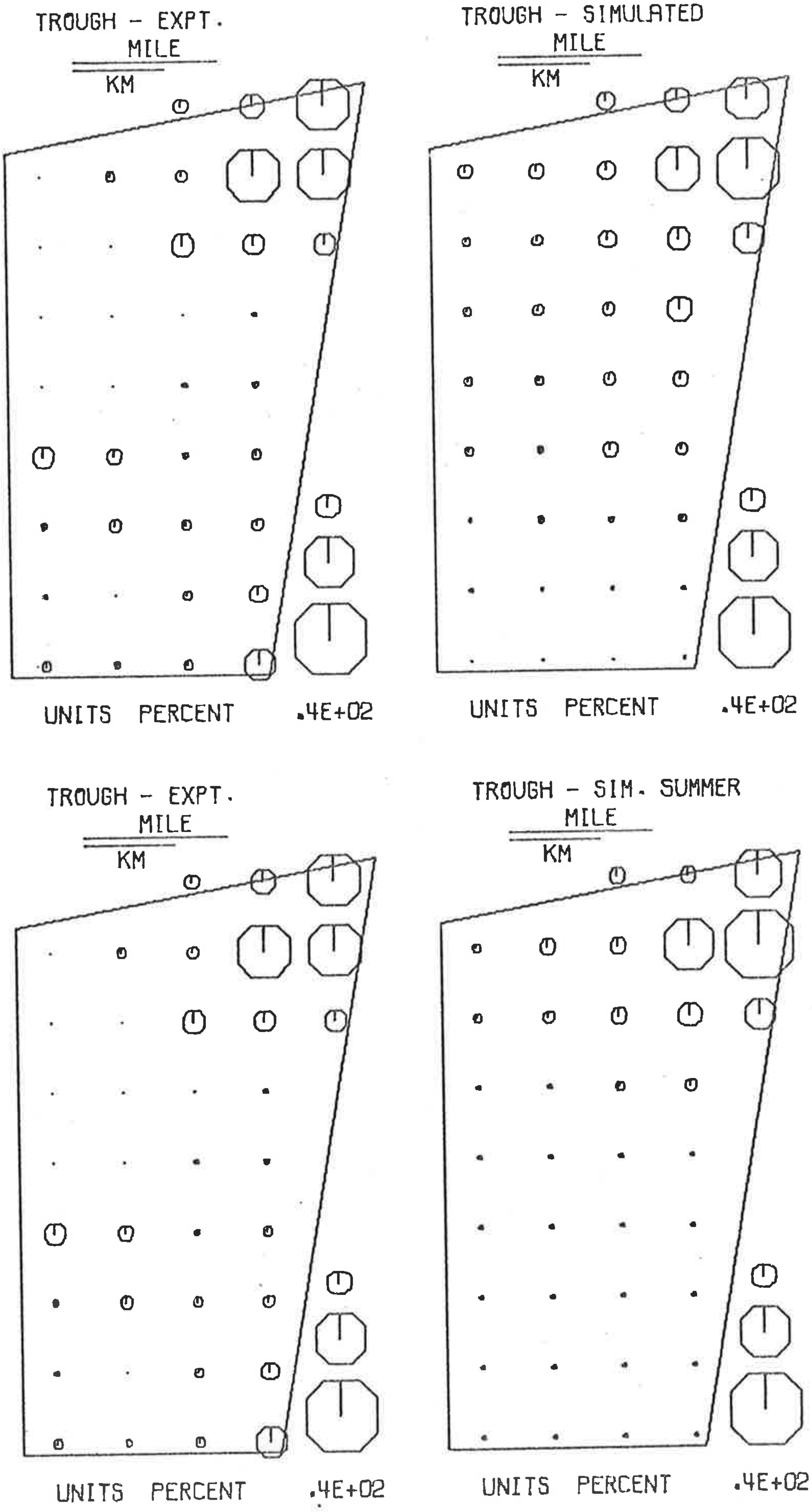


Fig. 8.19b. A comparison between the dung collected while the sheep were on the trough water-point and the model output described in section 8.53.

Symbols used in chapter 8

A ... surface area of the sheep (m)
alb_g ... albedo of the ground
alb_s ... albedo of the wool surface
B ... long wave sky radiation (W m^{-2})
C_a ... convective heat exchange from wool surface to air (W)
C_f ... conductive heat exchange from wool surface to body (W)
D ... damping depth (cm)
D ... day number in year
d ... diameter of the sheep (m)
EV ... evaporative heat exchange (W)
e ... vapour pressure of air (mb)
h ... hour angle (degrees)
h_c ... convective coefficient (W m^{-2} $^oC^{-1}$)
K ... thermal diffusivity of wool (cm^{-2} s^{-1})
k_f ... thermal conductivity of air (BtU hr^{-1} $^oF^{-1}$)
L ... length of the sheep (m)
LW ... live weight of the sheep (kg)
ME ... metabolic heat production (W)
m ... air mass number
n/N ... fraction of the daylight hours with a clear sky
Q, Q' ... short wave radiation on a horizontal surface (W m^{-2})
Q_A ... Angot's value, i.e. direct solar radiation above the atmosphere (W m^{-2})
Q_0 ... solar constant (= 1360 W m^{-2})
R ... radius of the sheep (m)
R' ... respiration rate (r min^{-1})
R_b ... long wave radiation from the sheep body (W)
R_g ... long wave radiation from the ground (W)
R_p ... heat exchange per respiration (W r^{-1})
R_s ... short wave radiation striking the sheep (W)
R_{sky} ... long wave radiation from the sky striking the sheep (W)
Re ... Reynold's number
r ... ratio of earth's distance from the sun to its mean value
S ... salt intake (g)

Table 8.1. The equations and symbols used in estimating the heat and water balance of a sheep.

T_a	...	air temperature (^oC)
T'_a	...	air temperature (K)
T_b	...	sheep body temperature (^oC)
T_s	...	wool tip temperature (^oC)
T'_s	...	wool tip temperature (K)
t	...	time of day (hr)
V	...	wind velocity (m s^{-1})
W	...	wool length (m)
W_d	...	water taken by drinking (l)
W_f	...	water taken in food (l)
α	...	solar altitude (degrees)
ΔT	...	temperature difference between wool surface and air (^oC)
ΔW	...	change in water balance (l)
δ	...	solar declination (degrees)
ε	...	eccentricity of the earth's orbit
ε, ε_s	...	emissivity of the wool tip surface
ε_w	...	emissivity of the experimental chamber
μ	...	dynamic viscosity of air (lb ft^{-1} hr^{-1})
ν	...	kinetic viscosity of air (ft^2 hr^{-1})
ρ	...	density of air (lb ft^{-3})
σ	...	Stefan-Boltzmann constant ($5.67 * 10^{-8}$ W m^{-2} K^{-4})
ϕ	...	latitude (degrees)
ω	...	angular frequency of the temperature oscillation

Table 8.1. continued.

Summary of the heat and water balance equations

Short wave radiation

$h = - 15 * (t - t_{noon})$ ... degrees

$\delta = 23.5 * \sin (360 * [D - 80] / 365)$ ... degrees

$\sin(\delta) = \cos(\phi) * \cos(\delta) * \cos(h) + \sin(\phi) * \sin(\delta)$

$^{1}/_{r^2} = 1 + 2 * \varepsilon * \cos (360 * D / 365)$

$Q_A = Q_0 * \sin(\alpha) / r^2$ ... $W\ m^{-2}$

$m = 1 / \sin(\alpha)$

$Q = Q_A * 0.9^m$ ... $W\ m^{-2}$

$R_s = k * R * L * Q$ ... W

k is a constant appropriate for the position of the sheep and the cloud cover

Long wave radiation

$B = 5.31 * 10^{-13} * T'^{6}_{a}$ ... $W\ m^{-2}$

$R_l = \varepsilon_s * \pi * R * L * (\sigma * T'^{4}_{s} - 1.04 * B)$ ... W

Convective heat transfer

$h_c = 4.62 * (V * d)^{0.805} / d$ ... $W\ m^{-2}\ {}^{o}C^{-1}$

Table 8.1. cont.

$$C_a = h_c * A * \Delta T \qquad \ldots \ W$$

Conduction through the wool

$$C_f = 0.402 * R * L * (T_s - T_b) / W \qquad \ldots \ W$$

Metabolic heat production

$$ME = 5.5 * LW^{\ 0.75} \qquad \ldots \ W$$

Respiratory cooling

$$EV = (0.58 - 0.0053 * Ta) * R' \qquad \ldots \ W$$

Change in water balance

$$\Delta W = W_d + W_f - 0.51 * R' - 0.03 * S - 0.09 \qquad \ldots \ l$$

Evaluation of the equations

$$\sigma * T'^4 \simeq 255 + 7.5 * T \qquad \ldots \ W\ m^{-2}$$

$$a = 25.4 * (V * R)^{0.805} / R$$

$$b = 0.402 / W$$

$$T_s = (k * Q - 357 + [28.7 + a] * T_a + b * T_b) / (23.1 + a + b) \qquad \ldots \ C^{o}$$

$$R' = (R * L * b * [T_s - T_b] + ME) / (0.58 - 0.0053 * T_a) \qquad \ldots \ r\ min^{-1}$$

Table 8.1. cont.

	Activity	Description
1	grazing	Most of the subflock is grazing, although a few sheep may be resting or ruminating. The subflock is usually moving as a whole at about 0 to 2 km hr^{-1}.
2	shading	The subflock is sheltering under & near some shade trees. Some of the subflock may not be in the shade, but are instead sheltering in the shade of other sheep.
3	camping	The subflock is resting or ruminating during the night at a site recognised as a camp.
4	resting	The subflock is stationary and most of the sheep are resting (lying or standing) or ruminating. A few sheep may graze intermittently. This activity is similar to 'shading' except that the subflock has not travelled to a shade site.
5-7	travelling	The subflock is moving in a group towards a particular destination. The average speed is about 2 to 3 km hr^{-1} and few other activities occur along the way.
8	drinking	Drinking at the water-point and resting immediately before and after.

	trigger	descritpion
1 & 3	dehydrated and thirsty	There are two levels of water deficiency. Thirsty sheep will not usually travel during the hottest time of the day, but if they lose more water and become dehydrated they will seek water despite the heat.
2 & 4	body temperature rising & hot	There are two levels of heat stress. Hot sheep will stop grazing and seek shade. They will move to water if they become thirsty. In more extreme heat stress they will not leave the shade unless they are suffering from dehydration.
5	night	It is assumed in the model that no grazing occurs from late evening until early morning.

Table 8.2. A description of the activities and triggers used in the sheep behaviour submodel.

6	hungry	...	Only one level of hunger stress is used in the behaviour submodel. The rate of consumption varies with hunger, but this is handled by the consumption submodel.
7	no stress	...	In this situation, the sheep rest wherever they happen to be.

Table 8.2. Cont.

trigger		present activity							
		1	2	3	4	5	6	7	8
						travel to			
		graze	shade	camp	rest	shade	camp	water	drink
1	dehydrated	7	7	7	7	7	7	7	8
2	body temp. rising	5	2	3	5	5	5	5	5
3	thirsty	7	7	7	7	7	7	7	8
4	hot	5	2	3	5	5	6	5	5
5	night	6	6	3	6	6	6	6	6
6	hungry	1	1	1	1	1	1	1	1
7	no stress	4	4	4	4	4	4	4	4

Table 8.3. The behaviour transition matrix. The new activity is given by the table entry corresponding to the present activity and the highest trigger set during the previous hour.

Condition stub	Condition entry						
hungry	-	-	-	-	-	Y	N
night	-	-	-	-	Y	N	N
hot	-	-	-	Y	N	N	N
thirsty	-	-	Y	N	N	N	N
very hot	-	Y	N	N	N	N	N
dehydrated	Y	N	N	N	N	N	N
rest							*
graze						*	
camp					*		
shade		*		*			
drink	*		*				
Activity stub	Activity entry						

Table 8.4. The decision table form of table 8.3. In choosing the next activity a column, matching the group of triggers set, is sought in the 'condition entry' part of the table (a dash [-] indicates that the trigger may be Y or N). The new activity is indicated in the 'activity entry' section of the table. This example does not include the travelling behaviour activities.

0.125	0.200	0.125	
0.110	↑	0.110	calm
0.110	0.110	0.110	

0.150	0.400	0.150	
0.080	↑	0.080	light
0.030	0.040	0.050	

0.100	0.600	0.100	
0.050	↑	0.050	strong
0.040	0.020	0.040	

Table 8.5. The probabilities used in estimating the effect of wind on the direction of movement during grazing. Each table represents the probability of travelling in any of eight directions measured (i), from the previous direction of travel in calm conditions, and (ii), from the direction from which the wind is blowing in light and strong winds. For example, in a strong wind there is a probability of 0.6 of moving into the wind and of only 0.02 of moving in the opposite direction.

SHEEP PHYSIOLOGY

9.0 *Introduction*

No original work, either in the form of experiments or model building, was attempted in the models of sheep maintenance energy, live weight changes, mortality, or wool production. As discussed in section 3.1, I had neither the appropriate background in this field, nor readily available facilities for experimental work. A simple model of these processes is included in the grazing model since they are an essential part of any grazing system description. It might be argued that these processes are the most critical section of the system since they represent the integrated reaction of the sheep to the many variables and because they include the parameters of major interest to the grazier, viz. sheep condition and wool production. However, as discussed in section 3.3 the main priorities in this study were those processes related to the spatial distribution of the impact of sheep on the vegetation.

I decided to review the nutritional models used in other grazing models, and their basis in the published literature, and from these to adopt a model most suited to the Middleback situation.

No literature review is attempted here, but the book by Blaxter (1962), and the review by Weston & Hogan (1973) give an adequate introduction to the enormous literature dealing with ruminant nutritional physiology.

9.1 *Nutrition and productivity models used in other grazing models*

The nutrition and productivity models used in other grazing models vary in their approach and detail, depending on the emphasis of the model. Goodall (1967, 1969) and Walters & Bunnell (1971) both use an empirical 'nutritional factor' to calculate the plane of nutrition of the animals, and from this estimated mortality and, in the latter case, fecundity.

Van Dyne (1969a), Swartzman & Van Dyne (1972), Vickery & Hedges (1972) and Smith & Williams (1973) all use more detailed models including metabolic energy requirements for maintenance, digestible energy intake and the efficiency of converting excess energy into live weight. Of these, the models of Vickery & Hedges and of Smith & Williams are the most detailed, and they apply to Australian conditions. They are very similar, since they are based on the same literature, and they were used as the basis of the model described below.

9.2 *The sheep nutrition and productivity model*

The main energy flows in the digestive and nutritional system of a sheep are shown in table 9.1. The organic matter intake is calculated in the sheep consumption model as described in section 7.4. The digestibilities of the 5 taxa included in the model would change with the growth phases throughout the year, but there was insufficient data available to include this in the model. Instead the digestibilities are treated as constants, with values as given in table 10.1. The energy content of the plant material is approximately 4.5 kcal g^{-1} (or $19 * 10^3$ J g^{-1}) (Odum, 1971). Therefore the DOMI and the DEI can be calculated for each day of grazing.

The mean DEI is calculated for the flock as a whole.

Even though each subflock is a discrete entity in the model, and it is possible to calculate the mean daily DEI for the individuals of the subflock, it is recognised that sheep transfer from one subflock to another when subflocks are near each other. Therefore separate sheep nutrition and productivity models for each subflock would have little meaning in the present version of the model.

It is assumed in the model thatthe metabolizable portion of the DEI is 81%, as in the Vickery & Hedges (1972) model. A large component (MERM) is used to maintain the body functions of the animal. This has been estimated as,

$$\text{(E9.1)} \qquad \text{MERM} = 63 * \text{LW}^{0.75} \qquad \ldots \text{ kcal day}^{-1}$$

$$\text{or} \qquad = 3.05 * \text{LW}^{0.75} \qquad \ldots \text{ W}$$

for a mature non-pregnant, merino sheep with a live weight (excluding fleece) of LW (kg) in a metabolic cage, or some similar environment (Weston & Hogan, 1973). However the energy requirements of free grazing animals are greater than for those indoors. The extra energy requirements of free grazing animals have been estimated in two ways. Graham (1964a) estimated the energy expenditure above maintenance, required for the activities of walking, feeding, ruminating and standing. If the duration of various activities, and the total distance walked are known, then the extra "work" costs can be calculated. However, it cannot be assumed that the MERM will remain unchanged in grazing sheep. Lambourne & Reardon (1963) found that the MERM was higher for sheep grazing abundant pasture than for the sheep, fed on the same pasture, but kept indoors. The MERM for sheep grazing sparse pastures was higher again. They argue that the increased MERM cannot be attributed to climatic effects, nor to the increased energy used in searching for and consuming sparse pastures. Similar conclusions were also drawn by Arnold _et al_. (1965).

Young & Corbett (1972) estimated the MERM for free grazing sheep, and found that it could be expressed as,

$$\text{(E9.2)} \qquad \text{MERM} = 45.1 * \text{LW} + 256 \qquad \ldots \text{ kcal day}^{-1}.$$

Their data was used as a basis for the models of Vickery & Hedges (1972) and Smith & Williams (1973) where,

$$\text{(E9.3)} \qquad \text{MERM} = 132 * \text{LW}^{0.75} \qquad \ldots \text{ kcal day}^{-1}$$

$$\text{or} \qquad = 6.4 * \text{LW}^{0.75} \qquad \ldots \text{ W.}$$

Young & Corbett argued that their results "show reasonable concordance" with the energy costs as predicted by Graham (1964b). If this is true, a model of energy expenditure could be included in the grazing model since the variables, total distance walked, grazing time, resting time and increased metabolism in cool weather are calculated. However, I cannot agree with their conclusion. When the activity estimates used by Graham for small enclosures are used to calculate the "work cost" of free grazing for sheep of the same live weights as used in the Young & Corbett experiments, the total energy expenditure at maintenance is as shown in the table below.

		weight (kg)	25	35	45
MERM (indoor)	(W)		34	44	53
small enclosure "work costs"	(W)		8	11	14
total energy expenditure	(W)		42	55	67
modified "work costs"	(W)		11	16	21
total energy expenditure	(W)		45	60	74
Young & Corbett's results	(W)		69	90	112

Even when the activity pattern is modified to include 7 hours grazing the estimated MERM is still 1/3 lower than the experimental results (modified "work costs" in the table). Therefore, it appears that there is some other avenue of energy expenditure as discussed by Lambourne & Reardon (1963). The equation based on the data of Young & Corbett (1972) (Equation 9.3) is used in the model since it appears to be the most soundly based equation for free grazing sheep, and the more detailed model is inadequate.

Further demands are made on the DEI for heat production. Young & Corbett claim that their sheep were little affected by heat or cold stress, so their estimate of MERM does not account for them. The sheep heat balance model calculates the increased metabolic rate in cold stress, but does not assume any increased metabolic rate in heat stress, as observed by Graham et al. (1959) in some conditions.

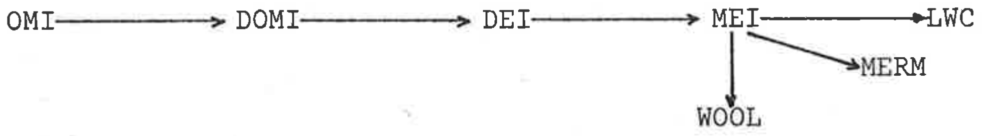
Wool production is an irreversible process and can be regarded as another energy demand on the sheep. Estimates of the energy required vary from 5.4 kcal g^{-1} (Vickery & Hedges, 1972) to 6.5 kcal g^{-1} (Young & Corbett, 1972). The lower value has been used in the model. Vickery & Hedges (1972) calculate the wool production from the MERM, but recognise that it is essentially a linear function of live weight. Their equations predict that the maximum annual clean, scoured wool production for a 50 kg merino under ideal conditions is 2.5 kg. This is much lower than the wool clips obtained in the Middleback area. The fleece weight in the Northern and Far Northern Statistical Divisions of South Australia in 1972 - 73, was 6.4 kg hd^{-1}, (South Australian Year Book, No. 9, 1974) and allowing for a 33% loss for cleaning and scouring (Weston, 1959) this yields 4.2 kg hd^{-1}. Langlands & Hamilton (1969) compared the wool production of several sheep breeds, including fine wool and strong wool merinos. Strong wool merinos, the most common in the Middleback area, were the most productive, producing 0.2 g day^{-1} for each kg body weight.

Many different relationships between wool production, and other variables have been proposed. Hutchinson (1960) found a linear relationship between forage intake and production, whereas Ferguson _et_ _al_. (1949) found an exponential relationship. However, forage intake is often correlated with other variables and thus correlations between these variables and wool production are also expected. For example Vickery & Hedges (1972) use MERM, while Williams (1964) correlated wool production with green forage on offer. I have assumed a linear relationship between wool production and body weight, with 0.2 g day^{-1} produced per kg of body weight. This rate was the maximum observed in experiments by Weston (1959), Langland & Hamilton (1969) and Young & Corbett (1972). The maximum yield estimated with this relationship is about 3.7 kg hd^{-1}. The relationship between the weight of the wool and the length of the staple is assumed to be linear and based on the data of Robards *et al.* (1974); the equation used is,

(E9.4) $$WOOL = WWOOL * 0.033,$$ ... m

where WOOL is the wool length, and WWOOL the fleece weight in kg.

Any excess of MEI over the demands described above is used in body weight increment, and any short fall is made up by body weight loss. The equations used by Vickery & Hedges (1972) for energy content of 1 kg of body weight and for the efficiency of conversion of energy to body weight and body weight to energy, are used in the grazing model. Similarly, the equations for sheep mortality described by Vickery & Hedges are used in the model. These equations give an annual mortality of 6% for sheep with body weights greater than 35 kg, and an increased mortality at lower body weights.



DEI	...	Digestible energy intake	Kcal day^{-1} or W
DOMI	...	Digestible organic matter intake	kg day^{-1}
LW	...	Live weight	kg
LWC	...	Live weight change	kg day^{-1}
MEI	...	Metabolizable energy intake	Kcal day^{-1} or W
MERM	...	Metabolic energy requirement for maintenance	Kcal day^{-1} or W
OMI	...	Organic matter intake	kg day^{-1}
WOOL	...	Wool length	m
WWOOL	...	Wool weight	kg

Table 9.1. The main energy flows in the digestive and nutritional system of a sheep. The abbreviations and units of the parameters used in chapter 9 are also shown.

THE COMPLETE MODEL

10.0 *Introduction*

This chapter describes the additions and modifications that were made to the submodels in linking them to form the final model. It also outlines some of the computing aspects of the final model.

10.10 *Additional sections*

10.11 *Spatial redistribution of nitrogen*

Nitrogen is redistributed throughout the paddock by the sheep in urine and faeces. Approximately 70% of the nitrogen excretion occurs as urine (Barrow & Lambourne, 1962) and this nitrogen rapidly becomes available for plant growth. The remaining nitrogen in the plant fragments in the faeces takes longer to break down than ordinary plant material (Barrow, 1961). The total amount of nitrogen excreted was estimated from total nitrogen intake less storage in the body or the fleece. The average daily intake of nitrogen was estimated from a run of the nearly complete model for 6 years, and was found to be 22 g hd^{-1} day^{-1}. The amount stored in the fleece amounts to about 1.5 g hd^{-1} $day^{-1}$and the storage in the body tissue in mature sheep is even less. This means that the sheep would redistribute about 15 g hd^{-1} day of nitrogen in a form readily available to plants. The amount redistributed would vary from day to day and hour to hour, and the pattern of redistribution would vary as the grazing pattern and total daily activity pattern changed.

A simplified nitrogen redistribution model is included in the complete model. Only the excretion of urine is followed and the rate is assumed to be constant from hour to hour, and to be 0.0007 kg hd^{-1} hr^{-1}. In all 'non-extensive' activities (see section 8.53) the urine is deposited in a limited area and would be of little use for plant growth. It is assumed therefore that a cell gains an input of available nitrogen, only when sheep are engaged in 'extensive' activity within it. The nitrogen losses from a cell due to grazing are accounted for in the plant intake submodel, and the other minor losses due to export from the paddock in fleeces and due to localized concentrations of nutrients, are ignored since these are small compared with the nitrogen turnover (see section 6.44).

The model showed that there was a higher concentration of available nitrogen in heavily grazed areas and in frequently used sites. This may have been due either to reduced demand for plant growth due to lower biomasses, or to the net importation of nitrogen by the sheep. The higher available nitrogen levels may have been a factor in the 'inverted piospheres' described in section 11.31.

10.12 *Shearing*

The complete model had to include a section to account for shearing. The most important action of this section is to reduce the fleece length to 0.002 m, and the fleece weight to 0.1 kg. The sheep are removed from the paddock for 5 days and the model is run with a stocking rate of zero for that time. The sheep are returned to the water-point in the morning of the sixth day, in a moderately hungry and thirsty condition. Stock losses due to death during the previous year are replaced by sheep assumed to be identical with those from the paddock.

In Wertigo the sheep are also removed for a few days for crutching. The effect of spelling the paddock for an extra 2 or 3 days per year would be small, and it is not included in the model.

10.13 *Plant water and salt content*

Plant water and salt are important parameters in estimating the water balance of the sheep (section 8.412). The total intake is estimated in the intake model (section 7.42). The plant water content and salt content varies throughout the year (e.g. Sharma et al., 1972), but there was not sufficient data available to include this. Instead constant water and salt contents, expressed as grams of salt or water per kg (dry wt.) of plant material (table 10.1) are used. The water contents are based on readings made in or near Wertigo at various times of the year, and the salt contents are based on the data of Lange (1967).

The digestibilities of the forage species are also presented in table 10.1 (see section 9.2). These estimates are based on values determined for similar forage types.

10.20 *Computing aspects*

This section briefly describes the computer program which implements the model described in the previous chapters. The program GRZMOD2 and the subroutines of the final model are listed in appendix 5.

10.21 *Program coding*

The program is written entirely in FØRTRAN IV as specified in the Control Data Corporation, 6000 series, version 4.1, FØRTRAN Extended reference Manual. The coding does not conform completely with the American Standards Institute (ANSI) FØRTRAN Language, but listings of all programs with ANSI incompatabilities flagged are held in the Botany Department, University of Adelaide. The differences are minor and there should be no problems in running the program on other large systems.

The GRZMOD2 program package consists of a main program and 25 (user supplied) subroutines, and makes use of systems supplied plotting, data manipulation and other subroutines. The program requires 60000_8 words of central memory for execution under the CDC 6400, Scope 3.4.1 operating system. At present it is designed to be run in batch mode, but it could easily be converted to operate in an interactive mode.

The printed output requires a 136 character line printer. The program also writes a string of important variables on to a file on a mass storage device (e.g. magnetic disc). It is easy to alter the variables included in the list, and the data can be collected either on each day of the simulation, or averaged over several days before being written on to the file.

The main program package has associated with it a group of smaller programs which further analyse the data saved on file. One package produces plotted output on either a 10 inch or 30 inch 'Calcomp' drum plotter, while another (DATAR) can be used in either batch or interactive mode to carry out statistical analyses or prepare further files.

The subroutines were maintained in a compiled form under the SCOPE 3.4.1 operating system 'user library facility'. This approach saved unnecessary recompilation of subroutines, while allowing easy correction.

The execution time for the programs compiled under the SCOPE 3.4.1, FTN optimized compiler (OPT=2) was 0.16 seconds per day of simulation. This could be reduced to 0.06 seconds per day if only one subflock of sheep was used in the sheep movement and behaviour section, rather than the usual ten subflocks. Six years of simulation (as used in the runs described in chapter 11) took 6 minutes of central processor (C.P.) time, and a complete run, including all the output and analyses took approximately 400 seconds C.P. time and would have cost approximately $A100 based on the University of Adelaide's present rates for external users (there was no charge for internal users).

10.22 *Program structure*

This section presents a broad outline of the program structure and the conventions followed in writing it. It is included as a guide to someone seeking clarification of points in the text and is not intended to be a complete description to be used by anyone wishing to modify the program or to implement it elsewhere as this would require another large document.

The program is split into 25 subroutines under the control of a main program. The names and purposes of these subroutines are listed in table 10.2. Data are transferred between these subroutines via 19 labelled COMMON blocks. The name of the COMMON block will usually indicate the subroutine it is mainly associated with. The names of all the important variables are invariant throughout the program.

A diagram of the structure of the program is shown in figure 10.1. I have not presented any form of flow chart since it would be so big as to be no more comprehensible than the program listing. The main program GRZMOD2 is a control program and is usually modified on each run. The main management options can be exercised via this routine, e.g. setting the stocking rate, changing the water-point and shearing date. Most of the parameters in the simulation can be altered by including the appropriate COMMON block in the main program and setting the new value in a FØRTRAN statement of the form,

```
PARAM = 0.0674      etc.
```

This will over-rule the default value set in a data statement elsewhere (usually in the subroutine BLKDATA). In this way the other subroutines of the package need not be compiled.

The package uses only one random number generating program supplied by the system. However it maintains four random number cores, one for each of the rainfall, temperature (and cloud), wind and movement behaviour simulations. This means that the random number streams are effectively independent of each other and they can be specified by the main program.

The 'core' subroutine of the package is DAYSIM which controls the simulation of a given period. It will call all the other routines necessary for the simulation, accumulate data and store or output them as required.

The structure of SHPMV is also outlined in figure 10.1 since it is a long and very important subroutine (e.g. it uses 75% of the C.P. time of a run) and it does not have a simple linear structure as do most other subroutines.

In chapter 2 I discussed the use of FORTRAN as a simulation language and pointed out some of its limitations. In this project the most frustrating limitations were problems associated with data accumulation and output. The data accumulating sections must be included among the simulation coding concealing the logic of the simulation. Several output utility programs were developed (e.g. PRINTAB and some of the 'Calcomp' plotting routines). These were of most use during the development and debugging stage but were gradually replaced by more specialized versions in the final package.

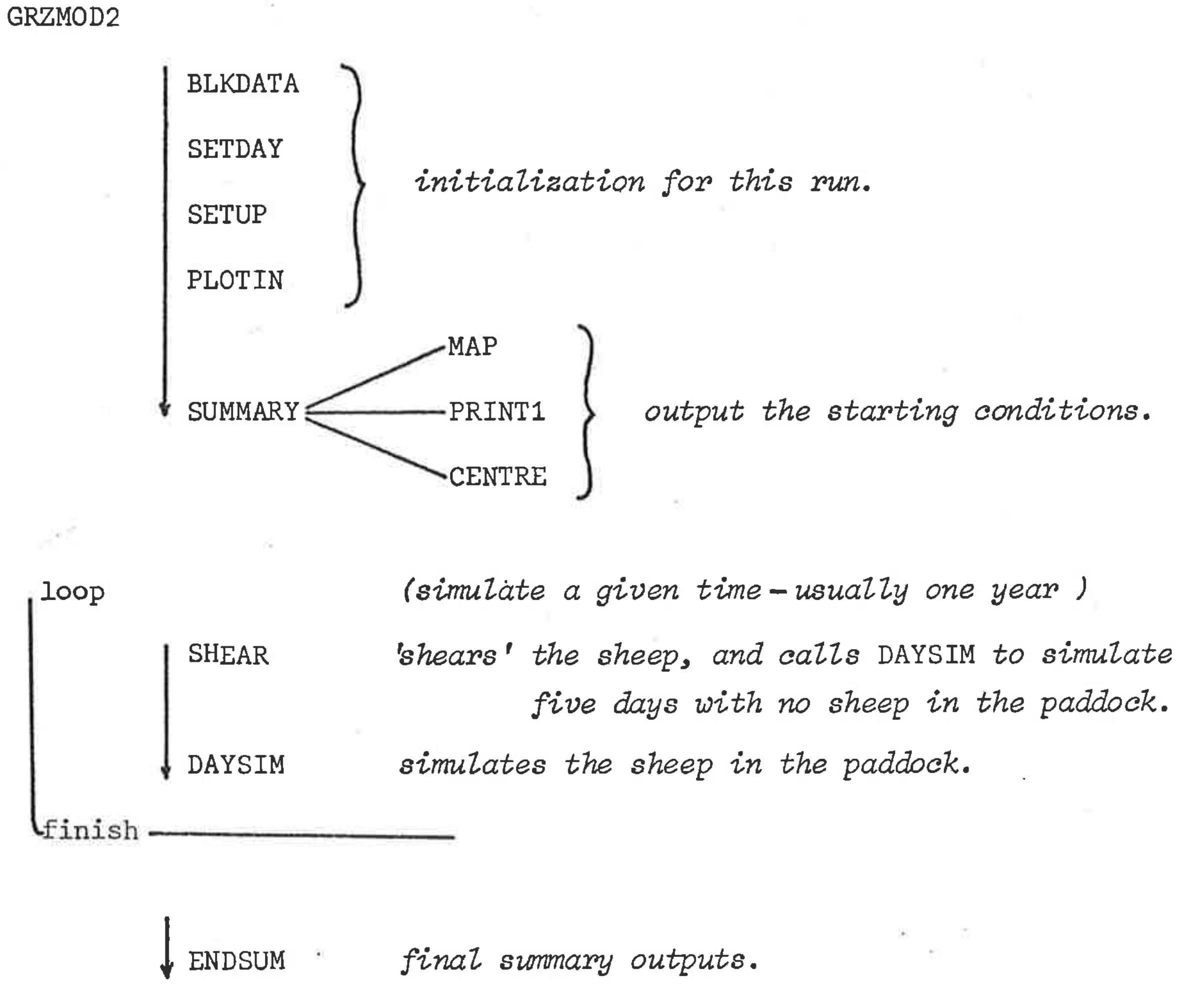


Fig. 10.1a. The structure of the main program "GRZMOD2". (Throughout this figure, names in block letters refer to subroutine names or entry points).

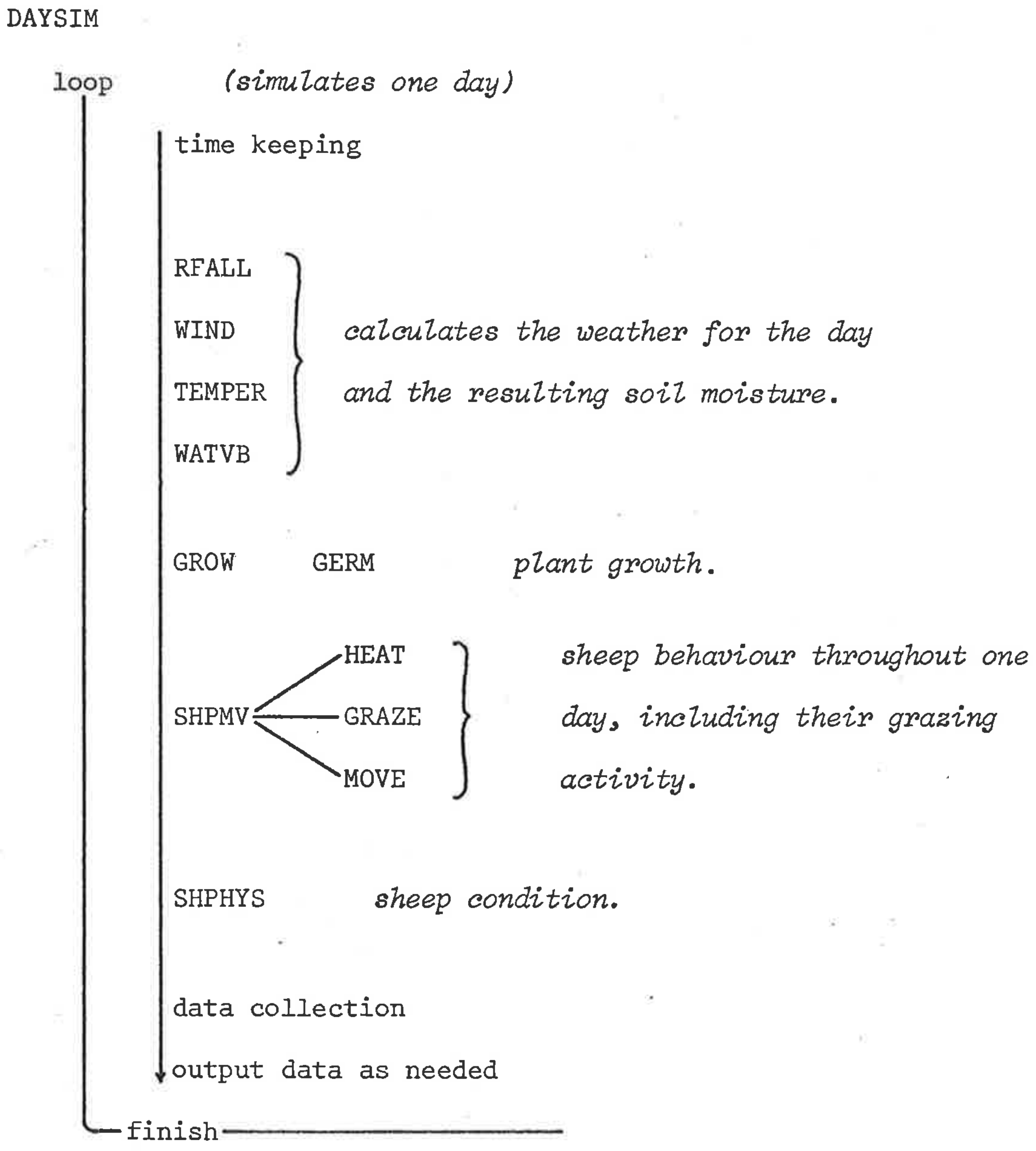


Fig. 10.1b. The structure of the subroutine "DAYSIM".

STRUCTURE OF SUBROUTINE "SHPMV"

```
SHPMV
          calculate the heat losses, hunger etc. during
          the night for all groups.

  loop               (simulate one hour)
          set the weather variables for the hour.

     loop            (for each subflock)
          calculate the heat balance —— HEAT (RESPRT)
          calculate the hunger.
          does their status allow them to graze —— GRAZE
                     (end of the hour)
          hunger flag?
          night flag?
          heat flags?
          calculate the water balance.
          thirst flags?

          select a new status
                     (begin the activities for the next hour)
          go to the appropriate activity.

          travelling          (calculate their new position)
          drinking            (reset water balance parameters)
          grazing             (keep a list of subflocks grazing)
     finish ——————

     loop            (for each subflock grazing)
          calculate the new position.
          do any other subflocks follow it?
     finish ——————

          are all the sheep in camp yet?  (i.e. the end of the day)
  finish ——————
```

Fig. 10.1c. The structure of the subroutine "SHPMV"

species	salt g/kg	water g/kg	digestibility kg/kg(dry wt)
grass	10.	1700.	0.7
bassia	40.	2600.	0.6
standing dead	25.	1000.	0.3
A. vesicaria	160.	1700.	0.8
K. sedifolia	110.	2600.	0.7

Table 10.1. The plant salt and water contents (section 10.13) and the digestibilities (section 9.2) used in the model.

Description of the subroutines used in GRZMOD2

BLKDATA	Sets the initial values for many of the parameters. (GRZMOD2)
CENTRE	Calculates the centre point of a distribution of values in the cells representing Wertigo paddock. (SUMMARY)
DAYSIM	Controls the execution of a day of simulated time. It also handles much of the data collection and plotting. (GRZMOD2 & SHEAR)
GERM	Calculates whether ephemeral germination has occurred. (GROW)
GRAZE	Calculates the plant consumption, plant water and plant salt intakes by the sheep. (SHPMV)
GROW	The plant growth submodel. (DAYSIM)
HEAT	Calculates the heat balance and respiration rate of a standard sheep. (SHPMV)
MAP	Prints small maps of the distributions of values in the cells representing Wertigo paddock. (SUMMARY)
MOVE	Calculates the position of subflocks as they are travelling. (SHPMV)
NUM	Utility routine used in line printer plotting. (PLOTTER)
PLOTTER	Performs line printer plotting. (DAYSIM)
PRINTAB	Utility routine used to print tables. (SUMMARY)
PRINT1	Prints biomass maps for WERTIGO. (SUMMARY)
RFALL	Calculates the daily rainfall. (DAYSIM)
SCALE	Utility routine, used for scaling for plotting etc. (various)
SETUP	Initializes arrays and performs some data analysis related to changes during the whole run. (GRZMOD2)
SHEAR	Shears the sheep. (GRZMOD2)
SHPHYS	Sheep physiology submodel. (DAYSIM)

Table 10.2 A brief description of the subroutines used in GRZMOD2. The subroutine which calls the subroutine being described is given in brackets at the end of each description.

SHPMV	...	Sheep movement and behaviour model. (DAYSIM)
SUMMARY	...	Produces a summary of the progress of the simulation since its last call. (DAYSIM & GRZMOD2)
TEMPER	...	Calculates the daily and hourly air temperature and cloudiness. (DAYSIM)
WATVB	...	The soil moisture submodel. (DAYSIM)
WERTMP	...	Plots, on a 'CALCOMP' plotter, maps of Wertigo paddock and the distribution of variables within the cells. (SUMMARY & SETUP)
WIND	...	Calculates the daily wind direction and velocity.

Table 10.2 continued.

EXPERIMENTS WITH THE COMPLETE MODEL

11.0 *Introduction*

This chapter describes a set of runs of the complete model. These runs were used partially for validation of the whole model, partially as a sensitivity analysis, and partially as management experiments. Validation of the model as a whole was not possible since no suitable set of data exists (section 4.5), and therefore the application of Turing's test must surfice. No attempt was made to perform detailed sensitivity analyses at this stage. They would be best done at the submodel level, and detailed analyses of each submodel were beyond the scope of the project. Instead the reactions to some parameters known to have broad scale effects on the model were investigated. In the management experiments proper, feasible management policies, which could be implemented with little financial expenditure or change to day to day activities, were emphasised.

The final runs performed are outlined in table 11.1, and they are discussed in the following groupings. First, validation via Turing's test is attempted in runs where the broad scale consequences of the treatment are well known. These include the effects of increasingly heavy stocking and of alternating the stock between water-points. Second, management experiments involving, stocking rates from 0 to 1000 sheep in the paddock, alternating the stock between water-points each year, and altering the shearing date, are discussed. Third, the sensitivity of the model to changes in mean annual rainfall and to the adaption of the sheep to the area via their plant preferences, watering, and travelling behaviour, is investigated.

11.1 *Integrative measures of sheep and paddock condition*

Integrative measures of sheep and paddock condition were needed to simplify the analysis and presentation of the experimental runs.

Wool production is an obvious measure of sheep condition since it is cumulative and directly related to the sheep live weight, and therefore consumption and behaviour, throughout the year. Furthermore, it is the parameter which is usually of most concern to the grazier. Wool production can be expressed as either mean production per head of sheep surviving the whole year, or as the total annual wool clip from the flock, thereby including sheep mortality in the measure. Wool production per head, total wool clip, and percentage mortality are used in the discussions below. Live weight is of limited value as a measure of sheep condition since it varies greatly throughout the year, and there is no special significance of high or low live weights in a particular season, as there is in a fat lamb enterprise.

A measure of vegetation condition poses more problems. Range condition and trend has been a major topic of discussion among range scientists for many years (Talbot, 1937), and many different field methods of condition assessment have been tried. Although a condition measure for the simulated paddock should take into account the same principles as the field methods, it must differ in detail due to the different types of information available. Most field methods attempt to measure the change from an ungrazed condition in terms of biomass, productivity, or 'desirability' of the plants (Condon, 1968; Noble, 1974).

Swartzman & Van Dyne (1972) used a range condition index in the optimization section of their model. Their index was based on live shrub numbers, a parameter not available in this model. Goodall (1969, 1971) used total forage productivity and total standing crop to compare treatments.

Measures of paddock condition based on biomass are more suited to this model. Simple variables such as total paddock biomass, total perennial biomass, or total biomass of a particular species could be used, but ephemeral biomasses are of little value since ephemerals have a short life span and a rapid regeneration time in suitable conditions. The spatial variation in biomass change is more useful than a single 'total paddock' parameter. Figure 11.3 includes maps of the paddock showing the distribution of the index,

$$I = [(B_{i,t} - B_{i,o}) / B_{i,o}] / [(\sum_j B_{j,t} - \sum_j B_{j,o}) / \sum_j B_{j,o}]$$

i.e. = (change in biomass in cell i from time 0 to time t, as a proportion of the starting biomass) / (change in biomass of all the cells from time 0 to time t, as a proportion of the total starting biomass).

This index takes negative values in areas where the vegetation shows a change worse than the paddock as a whole, and is positive elsewhere. These maps are useful for assessing, at a glance, the distribution of intense paddock use. Lightly grazed paddocks should show a scatter of positive and negative values due to local variations in growth rate. As the grazing pressure increases, the more heavily grazed sites would show increasingly negative values and the more lightly grazed sites increasingly positive values, leading to a change in both magnitude and distribution of the index.

Such maps, however, are clumsy to present and compare. Therefore a single index taking into account both the biomass and its availability to the sheep would be useful. One approach is to use an index based on the weighted average biomass of a suitable indicator species or group of species. The weighting variable in the model output could be grazing time per cell since this is available on every run, however, it will vary from one run to another according to management policy, weather conditions and as the distribution of the vegetation itself changes. Nor is grazing time usually available in real situations, and it would be advantageous to have an index that could be applied in the field. However, there is a strong correlation between grazing time and distance from water in all runs of the model. Figure 11.1 shows that the simulated grazing time per unit area is linearly related to the reciprocal of the distance from water. This implies that the mean time spent in each annulus centred on the water-point is the same since the area of an annulus increases in direct proportion to its distance from the centre. An index was proposed, where the biomass of each cell was weighted by the factor $1/d_i$

where d_i is the distance of the centre of the i th cell from the water-point. When the management scheme used two water-points the index was calculated for both and the average was used. A related index, which allowed for the change in total paddock biomass, was also used. The indices, hereafter referred to as 'piosphere indices', are,

$$p'_t = \sum_i (b_{i,t} / d_i)$$

and, allowing for changes in total biomass,

$$p_t = \sum_i (b_{i,t} / d_i) / \sum_i (b_i).$$

Practice showed that $\Delta p'_t$ and Δp_t, representing the difference between the piosphere indices for the experimental run and a standard run with no sheep (see run R-1, described in the next section) were more useful. These indices were calculated for *A. vesicaria* since this is the species which best displays the piosphere effects. The properties of the indices are discussed in section 11.32.

A. vesicaria, *K. sedifolia* and total perennial biomass are also given in table 11.2. They are included not only because of their importance as a fodder reserve but also as an indication of the paddock's resistance to erosion since erosion has been shown to be a function of cover (Marshall, 1970). Although ephemeral cover is also effective in erosion reduction, only the perennial cover can be relied upon to be there at all times of erosion susceptability.

Total paddock biomass of perennials does not give any indication of the potential for localized sites of erosion due to bush removal. This could have been estimated by a piosphere index based on perennial biomass rather than *A. vesicaria* biomass alone, but it was not calculated. I recognised that no index or set of indices would be completely adequate and I thought that, in this first examination of the model, the number of indices should be small.

11.2 *The model runs*

The model was run 18 times using the same initial conditions in each case, and in 14 runs the same weather pattern was used. The model was known to be very sensitive to the amount and timing of the rainfall, so a standard weather pattern was chosen from a series of runs of the rainfall submodel alone. Each run was six years long and used a different random number core. The first run with a mean annual rainfall within ± 10% of the Middleback mean was used. The run which met these requirements had a mean annual rainfall of 208 mm. An high and a low rainfall sequence were also chosen by taking the next runs with a rainfall 10% to 20% less than or greater than the standard weather sequence.

The seasonal distribution of the rainfall is shown in figure 11.2. The first 4 years had approximately average rainfall but they were followed by a 15 month drought which did not 'break' until the last summer of the sequence. The same temperature, solar radiation and wind sequences were used in each standard weather sequence.

The initial conditions were based on Wertigo paddock in October 1972. The mean perennial biomass in each cell was set to the biomass recorded at each of the 37 quadrats estimated on the above data, and the ephemeral biomass was set to 50 kg ha^{-1} of both grass and bassia with no standing dead material (fig. 11.4). The total biomass in the paddock was 1347 t, i.e. an average of 569 kg ha^{-1}. The soil moisture was set to the wilting point in each layer.

The number of sheep varied from run to run. The sheep were assumed to have been just shorn and were placed in the paddock at the water-point, 'moderately' thirsty and hungry.

A run with no sheep was carried out. The resultant total plant biomass is shown in figure 11.2. There is no net trend in the total biomass but both the perennials showed a tendancy to increase. The mean annual growth rate over the 6 years was 8.6% for *A. vesicaria* and 5.4% for *K. sedifolia*. The details of this and other runs will be discussed below.

The runs carried out, the treatments, and the code numbers and symbols used in referring to these runs for the remainder of the thesis are presented in table 11.2. An example of the printed output is presented in appendix 6, and the plotted outputs from some of the runs are presented in figure 11.3. The interpretation of the outputs is described in detail at the beginning of appendix 6.

11.30 *Discussion of the model runs*

11.31 *Validation*

A complete set of printed and plotted output was produced on all runs, and was examined in each case. They are too bulky to include in this thesis since they include approximately 1200 pages of printing and 600 individual plots and graphs. The major strengths and weaknesses of the submodels were described in the appropriate chapters and are not discussed again here. No unexpected results arose from the added interactions in the complete model.

Figure 11.3 shows the results of run R-2 which was taken to represent the normal management practice of set stocking 300 sheep on the dam water-point (hereafter called the 'standard run'). The sheep consumption, walking and drinking behaviour is in general agreement with our present understanding of the system. The sheep live weights and fleece production may be too low for the large bodied merinos run in the area. This is essentially a problem of scaling. A higher live weight would result in a higher fleece production, but in turn would require a higher consumption and therefore a greater impact on the vegetation. However, the model is only affected by total consumption and therefore 300 sheep eating 1.0 kg hd^{-1} day^{-1} is equivalent to 250 sheep eating 1.2 kg hd^{-1} day^{-1} in terms of impact on the vegetation. The wool production would be very similar, although not identical, because, while wool production is directly proportional to live weight, live weight is not directly proportional to consumption. Nevertheless, the apparently low live weights and fleece productions are not serious problems in interpreting the results of the modelled experiments.

A more important weakness in the model is the rate at which the piosphere develops. Wertigo has remained in a relatively stable condition while being grazed by flocks of about 300 sheep on the dam water-point for many years. Therefore, although a piosphere should already be impressed on the vegetation, it too should be stable under similar conditions. In the model the existing piosphere shows up in the depressed *A. vesicaria* biomasses used as the initial conditions for the cells near the dam (fig. 11.4). However, the simulated grazing results in even further decrease in biomass in the cells near water, and apparently at a rate faster than is occurring in Wertigo. This implies that the simulated grazing is concentrated too heavily about the water-point, as was suggested during the validation of the sheep movement model (section 8.53). The sheep probably avoid areas that have already been subject to heavy grazing, so reducing the grazing pressure and lessening the deterioration. The model includes no such mechanism except the simple factor described in section 8.420. This part of the movement and grazing model needs to be expanded either by finding empirical relationships better than those used in section 8.420, or by including a learning model to modify the movement and grazing behaviour of the flock.

However, it should be borne in mind that piospheres can be impressed on the vegetation very rapidly. Figure

11.5 summarizes the impact in Wertigo of a flock of 450 sheep (300 ewes and 150 lambs) on the trough water-point from November 1972 to February 1973. This was the first time this water-point had been used by a large flock and since sheep watering on the dam rarely reach the trough area, the vegetation would not have shown any major sheep effects. Unfortunately no readings were taken until May 1973, three months after the flock had been removed from the trough. The rains which occurred in February 1973 washed the dust from the vegetation and caused the healthier bushes to sprout making the estimation of mortality easier. The exceptionally heavy rains of 1973 and 1974 meant that the surviving bushes recovered quickly as was shown by the second set of readings in October 1973. Biomass and mortality of *A. vesicaria* and *K. sedifolia* were estimated in 20m x 1m quadrats at intervals along three transects from the trough. Two transects (azimuth 335° and 360°) were in Wertigo, and the third (azimuth 40°) in the lightly grazed, neighbouring paddock. These were the only bearings that gave long transects through non-wooded areas.

A. vesicaria reflected the impact of grazing much more than did *K. sedifolia* and it was used to estimate the development of the piosphere. The increase in bush mortality extended at least 500 m from the trough in May, and by October increased mortality extended to approximately 1000 m. The biomass increased with distance from water for the full length of the transect (i.e. to the fence). It is possible that a gradient in biomass was present before the grazing, but this seems unlikely to be the major effect in view of the uniform vegetation on the other side of the fence. The bushes also showed obvious signs of grazing which decreased with distance from the trough demonstrating that the grazing was the major effect.

Therefore it is clear from this limited study that a piosphere extending over a 1000 m from water can be impressed on the vegetation in a short time. Although the modelled piosphere developed rapidly, it is not unrealistic. The model also agrees with the real situation in that *K. sedifolia* is much less affected by grazing and shows little or no piosphere pattern.

Other minor points appearing during the experimental runs added further support to the model as a whole. For example, the distribution of available nitrogen in the soil tended to be higher in the heavily used areas. Such processes have been discussed by several authors (Hilder, 1964), but have not been tested in Wertigo. The aspect which lends support to the model is that realistic changes in available nitrogen occur even though the model was not 'fitted' to produce the result. The nitrogen redistribution in the model was based on deductions from sheep behaviour and physiology.

Another example, is the occurrence of 'inverted piospheres', i.e. a palatable species being distributed with its highest biomass near the water-point. These species are not 'increaser species', as are often discussed in the literature, since at most times they show the normal piosphere effect. Several examples of 'inverted piospheres' occurring during growth periods have been described by Fatchen (unpublished Ph.D. thesis, 1975). In the model bassia sometimes shows an 'inverted piosphere' during growth phases. This is probably due to a reduction in competition from the more preferred grasses in the heavily grazed areas, although higher nutrient levels may also be a factor.

11.32 *Management*

Three different aspects of paddock management were examined in the experimental runs. The first was the effect of different stocking rates; the second, the effect of using different water-points in alternate years; and the third, the effect of changing the shearing date.

Runs were carried out with the stocking rate set to 0, 50, 300, 600 and 1000 sheep on the dam water-point. It is realised that set stocking with 0 or even a 1000 sheep is not a "feasible management policy" as mentioned in section 11.0. Instead the runs were intended to produce a base line of grazing effects against which other treatments could be compared. The optimum stocking rate under a given management policy could not be determined. The problems in scaling the sheep effects, as discussed in the previous section (11.31) would make any specific, optimum stocking rate invalid, even if an optimum trade off of paddock condition and sheep production could be decided upon. The optimum stocking rate would also vary with the weather experienced and therefore many runs with different weather sequences would have been necessary in order to determine the distribution of outcomes. More complicated management schemes, such as grazing the paddock only in alternate years or adjusting stocking rates in response to the paddock or sheep condition, were not investigated, since they too would require many runs.

The range of stocking rates was taken as a basis for comparison of different treatments since it is a simple concept and anyone with some experience of the area can picture, to a degree, the effects of different stocking rates. It is also already commonly used by graziers as a basis for comparison, although more usually as sheep per unit area, rather than sheep per water-point as used here. The Pastoral Act of South Australia uses stocking rates (sheep equivalents per square mile) in the covenants of the Act.

Figure 11.6 summarizes the relationships between the indices of sheep and paddock condition and the stocking rate. *A. vesicaria* biomass, Δp_t and $\Delta p_t'$ show very nearly linear relationships with stocking rate, while wool production, although clearly non linear, does not vary greatly from the linear relationship. Although a linear relationship between the indices and the stocking rate is not essential for the interpretation of the results, it is an advantage since the indices and stocking rate are directly interconvertable and the indices show a uniform sensitivity over the full range of stocking rates used here.

The sequence of runs at different stocking rates demonstrated the importance of the ephemeral component of the vegetation. Figure 11.7 compares the standard stocking rate (300 sheep) and the most extreme stocking rate (1000 sheep) with the unstocked situation. In the standard run, all of the *K. sedifolia* loss and much of the *A. vesicaria* loss, occurred during the latter part of year 5 and early in year 6, that is, during the periods of declining and low ephemeral biomass. The same pattern appeared in the 1000 sheep run, although bush losses were higher and more continuous.

The run using the trough water-point (R-3) shows the effect of paddock geometry and perennial distribution on the sheep production and on the piosphere effect (fig. 11.3, and table 11.2). The trough is in the corner of the paddock, restricting the movement of the sheep to a smaller area. This results in a greater impact on the vegetation as measured by Δp_t since the cells near the water-point suffer almost a total loss of *A. vesicaria*. However this concentration of grazing reduces the impact in the rest of the paddock and the *A. vesicaria* loss as a whole is reduced, as is reflected on the total *A. vesicaria* biomass and the $\Delta p'_t$ index.. This effect was further emphasised by the initially low *A. vesicaria* biomasses near the water-point and the initially high *K. sedifolia* biomasses. The sheep were forced to consume less *A. vesicaria* and more *K. sedifolia*, and this, coupled with a lower intake of live ephemerals due to the restricted range of grazing, reduced the wool production by 2 to 3%.

The effects of alternating the water-point in use each year was investigated since in Wertigo the water-points were sufficiently far apart for this to be equivalent to spelling the most heavily grazed areas every second year. Alternations begining at both the dam (D-T, R-7) and the trough (T-D, R-8) were run in order to minimize the seasonal effects as discussed above.

The treatments had little effect on the wool production or even on the perennial biomasses, but they did reduce the piosphere effect (fig. 11.3). This reduction is expected since the indices are the average of two piospheres which have had only half the grazing pressure of a single water-point run. The impact on the vegetation was equivalent to 140 sheep and 200 sheep set stocked on the dam in terms of Δp_t and $\Delta p_t'$ respectively.

One run, in which sheep were grazed at the highest stocking rate (1000 sheep), but alternated on the water-points (D-T) was carried out. The results were similar to the runs with the stocking rate of 300 sheep. The treatment was equivalent to set stocking of 280 sheep and 540 sheep for Δp_t and $\Delta p_t'$ respectively.

In summary, the model indicates that although alternating the water-points in use will decrease the intensity of piosphere development, it has little effect on sheep production or total perennial biomass. However, the reduced piosphere effect must mean that in periods of stress (i.e. high temperatures or few ephemerals), the sheep will have more food available to them near the water-point, and therefore should lose less condition. This is borne out, in that the sheep production figures are marginally (< 1%) higher in the alternating water-point trials, than in the set stocking trials. It is dangerous to place too much emphasis on such small differences due to the many interactions not included in the model. For example, what effect does the grazing pressure have on the ephemeral seed bed and germination? Or, do the less intense piospheres produce a larger 'B zone' as described by Osborn et al. (1932) and is this zone more productive?

The effect of changing the shearing date from March to 6 months later, in September was also investigated. This is a feasible alternative to the present management scheme, but it would require major revisions of other station activities such as lambing dates, and it would be dependent on the availability of shearing teams. March is the driest month at Middleback, and this is an advantage in the shearing period. September also tends to be colder than March and sheep losses due to exposure would be more likely. However, the sheep would be carrying shorter fleeces during the early summer period when grass-seeds and blowflies can become a problem. I also suspected that shorter fleeced sheep may be able to withstand the summer conditions better. Other stations in the South Australian arid zone shear on dates ranging from autumn to spring.

The model was run with the standard weather sequence, but with shearing occurring every September (R-10). The sheep were shorn in both March and September of the first year and again in March of the final year. The treatment had very little effect on the condition of the vegetation, but the wool production increased by 3%.

A more detailed examination of the results shows that the difference in sheep productivity is due to a higher mean consumption by the September shorn sheep (table 11.3). The September shearing reduces the heat stress on the sheep and enables them to spend longer hours grazing during the spring and summer. It has been argued (e.g. Macfarlane *et al*., 1966) that a long fleece reduces the heat stress of a sheep. This is true in very hot conditions (high radiation loads, and air temperatures greater than body temperature), but, as discussed in section 8.416, in lesser (and more frequent) heat stress conditions, shorter fleeces are more suitable. In spring the newly shorn sheep do not need to drink as frequently and therefore spend more time grazing, while in summer both groups of sheep drink with the same frequency, but the September shorn sheep apparently need to spend less time in the shade. The March shorn sheep have a similar advantage in autumn and winter, but this is not as useful in maintaining body weight and wool production. Spring tends to be the peak of the ephemeral growth season and therefore increased grazing at this time tends to result in higher body weights, than does longer grazing on autumn and winter forage.

Since alternating the water-points reduced the piosphere impact without affecting wool production, and the September shearing increased wool production without affecting the piosphere impact, it seemed logical to combine the two treatments, as in run R-18. The results showed that the piosphere impact is comparable to the alternating water-point runs (fig. 11.3), and the perennial biomasses are even marginally better than these runs. The improved vegetation condition occurred while maintaining the high wool production associated with the September shearing.

Therefore, it would appear from the results of the model that an improved management scheme would include September (spring) shearing and the alternation of water-points. However the magnitude of these effects should be borne in mind. The difference in total perennial biomass between the treatments is only 1 to 2%, and the change in wool production is 3%. Therefore, given the qualifications that need to be made in presenting any of the model results, it is doubtful whether much reliance can be placed on the exact magnitude of these changes, although some insight is gained about the mechanisms involved in the treatments. More importantly, it becomes apparent that any improvement that might be gained in both vegetation condition and sheep productivity is very small when compared with the year to year fluctuations due to different weather patterns.

11.33 *Sensitivity*

The response of arid zone vegetation to high rainfall is both dramatic and rapid, while the response to drought conditions is slower but equally dramatic in the contrast with better seasons. Condon et al. (1969) in their method for the quantitative assessment of carrying capacity in central Australia gave greatest emphasis to mean annual rainfall, while the few long term, Australian arid and semi-arid research projects aiming to measure the effect of grazing on the vegetation have all found that the rainfall response tended to mask the grazing response (for example Biddiscombe, 1956; Williams 1968; Trumble & Woodroffe, 1954; and for further discussion, Noble, 1974). The difficulties in conducting and interpreting long term grazing trials arises both because of the response of the vegetation to rainfall, and because of the rainfall variability of the area. For example, in the Australian arid zone a five year grazing trial has only a 50:50 chance of receiving an average rainfall within 10% of the true annual mean, while a third of all ten year trials will vary from the mean annual rainfall by more than 10% (Noble, 1974).

The sensitivity of the model to rainfall was tested in two ways. Runs with different climatic conditions selected for high (R-14) and low (R-13) rainfall were attempted (section 11.2 describes the selection), and also the standard run was repeated first with each fall increased by 10% (R-11), and then with each fall decreased by 10% R-12.

Runs R-13 and R-14 (i.e. high and low rainfall with 300 sheep on the dam) show the effect of both a change in the amount of rainfall and in its timing. The high rainfall run had 18% more rainfall than the standard run, but had 45% more perennial biomass after 6 years. The low rainfall run had 13% less rainfall, but still resulted in marginally better vegetation condition and sheep production, demonstrating the importance of the timing of the rainfall. The rainfall in the low run was more evenly distributed than it was in the standard run.

Runs R-11 and R-12 were used to examine the effect of a change in rainfall amount, without a change in timing. The results are summarized in fig. 11.8 which shows the percentage change of various parameters plotted against the percentage change in rainfall with all values compared to the standard run. The bush biomasses tend to be very sensitive to changes in rainfall, with *K. sedifolia* showing a 66% change in biomass, and *A. vesicaria* a 51% change with the 20% change in rainfall. However, *A. vesicaria* is much less sensitive to increased rainfall above the standard run, than to reduced rainfall. The changes in bush biomass are reflected in the change in $\Delta p_t'$ which shows 135% change. The sheep are much less affected by the change in rainfall. The wool production changed by only 5% over the 20% rainfall range. This result is not unexpected, since the vegetation was initially in good condition and the only effect that the change in the amount of rainfall has over a 6 year period is a small change in the amount and duration of ephemeral availability. This leads to only small changes in the nutrition of the sheep.

The sensitivity of the model to changes in the characteristics of the sheep used was tested in 3 runs. In run R-17 the sheep were made to walk greater distances than normal. This was done by changing the probability that they would move to a new cell during each hour of grazing from 0.4 and 0.7 to 0.7 and 0.9 (section 8.421), and increasing their speed of travelling to water, shade or camp from 2 to 3 km hr^{-1}. This resulted in sheep that showed a more extensive pattern of grazing and increased the mean distance walked per day from 8.00 to 8.93 km. The increased amount of walking was unifromly distributed throughout the year. Differences of this sort have already been noted between different sheep breeds (e.g. Squires & Wilson [1971] with border leicesters and merinos), so the run may be considered as an experiment with a 'walker' breed.

The results are summarized in tables 11.2 and 11.4. The 'walker' breed spent a little less time grazing than did the normal sheep, but the total consumption remained the same. However the wider ranging of the 'walker' sheep allowed them to select a more preferred, and more nutritious, diet, with an increased consumption of ephemerals and *A. vesicaria*. This resulted in a 2% increase in wool production and a less intense grazing impact near the dam (Δp_t only -0.028 compared with -0.031 in normal conditions, table 11.2). Therefore, despite a 12% improvement in walking, the new breed gave only very small improvements.

The grazing activities of sheep could be spread more evenly over the paddock if they were less dependent on the water-point. Run R-16 experimented with a breed of sheep which needed to drink less frequently. This was included in the model, by allowing the sheep to drink to a fill of 5.0 l of water at each drink rather than 4.0 l as in the normal sheep (section 8.412). Alternatively this could be considered as a 20% reduction in water demand for all physiological processes (which is rather unrealistic), or as a breed of sheep which will tolerate greater dehydration than usual.

The results are summarized in tables 11.2 and 11.5. This run also showed reduced grazing pressure near the water-point, but the sheep did not graze as widely as the 'walkers'. Therefore, there was a smaller impact on the *A. vesicaria* than in run R-17, but the diet selected was still more nutritious than in the standard run, and wool production was increased by 1%.

The previous experiments had demonstrated that the wool production of the sheep is dependent on the quality of the diet selected. Therefore another run (R-15) was carried out with the sheep preferences for the ephemeral species (p_i values of section 7.41) increased as shown below.

	standard runs	R-15
grass	3.0	12.0
bassia	1.25	5.0
standing dead	0.5	2.0
A. vesicaria	1.0	1.0
K. sedifolia	0.1	0.1

(see table 7.3)

This would result in a less nutritious diet since the sheep would eat less of the highly digestible *A. vesicaria*, but they should also have a lower intake of salt.

The results are summarized in tables 11.2 and 11.6. The sheep consumed 0.03 kg more food each day, but this included 0.16 kg more ephemerals. Only small changes in grazing time and walking occurred, but the sheep drank much less frequently than in the standard run. The grazing impact as measured by Δp_t and $\Delta p_t'$ was very much reduced, as was expected. However the wool production was also reduced. In good conditions the ephemeral preferring sheep did as well as the sheep in the standard run, but in poorer conditions they selected more standing dead material rather than the more nutritious bush. They suffered a major loss of live weight and wool production in years 5 and 6 of the run.

In summary, the paddock system as simulated in this model is most sensitive to changes in both rainfall amount and timing. The vegetation response is very sensitive, with all the indices showing a greater percentage change than the percentage change in the amount of rainfall. The response of the wool production is very much less since the sheep condition is buffered by various compensating mechanisms.

The 'new breeds' of sheep had significant effects on the condition of the vegetation but much less on the wool production. It is interesting to note that none of the new breeds showed as much improvement in wool production as the change of the shearing date.

11.34 *Summary*

The experimental runs indicated that the model output appeared to be reasonable in all the aspects investigated. However the predicted changes in productivity and vegetation condition due to different management policies are small, especially when compared to changes due to the natural variability of the system. This implies that the predictions of the model concerning comparative management policies should be treated with caution given the qualifications that must be made in presenting the results of an untested and unrefined model as this one is. However it also implies that the management options available to the grazier are limited. It appears that most options (other than heavy overstocking) will produce changes much smaller than the vagarities due to the weather pattern and especially the rainfall.

The model displays a realistic complexity of interactions and day to day variability as is evidenced by the discussions of the submodels and in the complete model runs. It should therefore prove useful in investigating possible lines of research and ways of simplifying subsequent grazing system models. One such approach is discussed briefly in the next section.

11.4 *Linear relationships*

In sections 4.4 and 8.54 I discussed the possibility of improving the model by replacing some of the more detailed structure by simpler empirical relationships. This would be especially useful in the sheep behaviour section. Patten (1972) has also argued that linear methods are sufficient for characterizing ecosystem dynamics, at least given the amount of information available at present.

As discussed in section 10.21, a string of parameters was written by the model program on to magnetic storage at regular time intervals. These data could then be analysed by the program package DATAR. Only a few analyses have been done and initially the emphasis was on those aspects concerned with sheep behaviour and movement. Figure 11.9 is an example of some of the output produced on each run of the model. A brief study of the parameter pairs listed in table 11.7 indicated that all showed significant linear relationships in almost all runs, although some of the relationships could better be described by non-linear equations. These results indicate that it would be possible to develop empirical models of sheep movement and consumption behaviour based on this more detailed model, however there has not been time to follow this any further in this project.

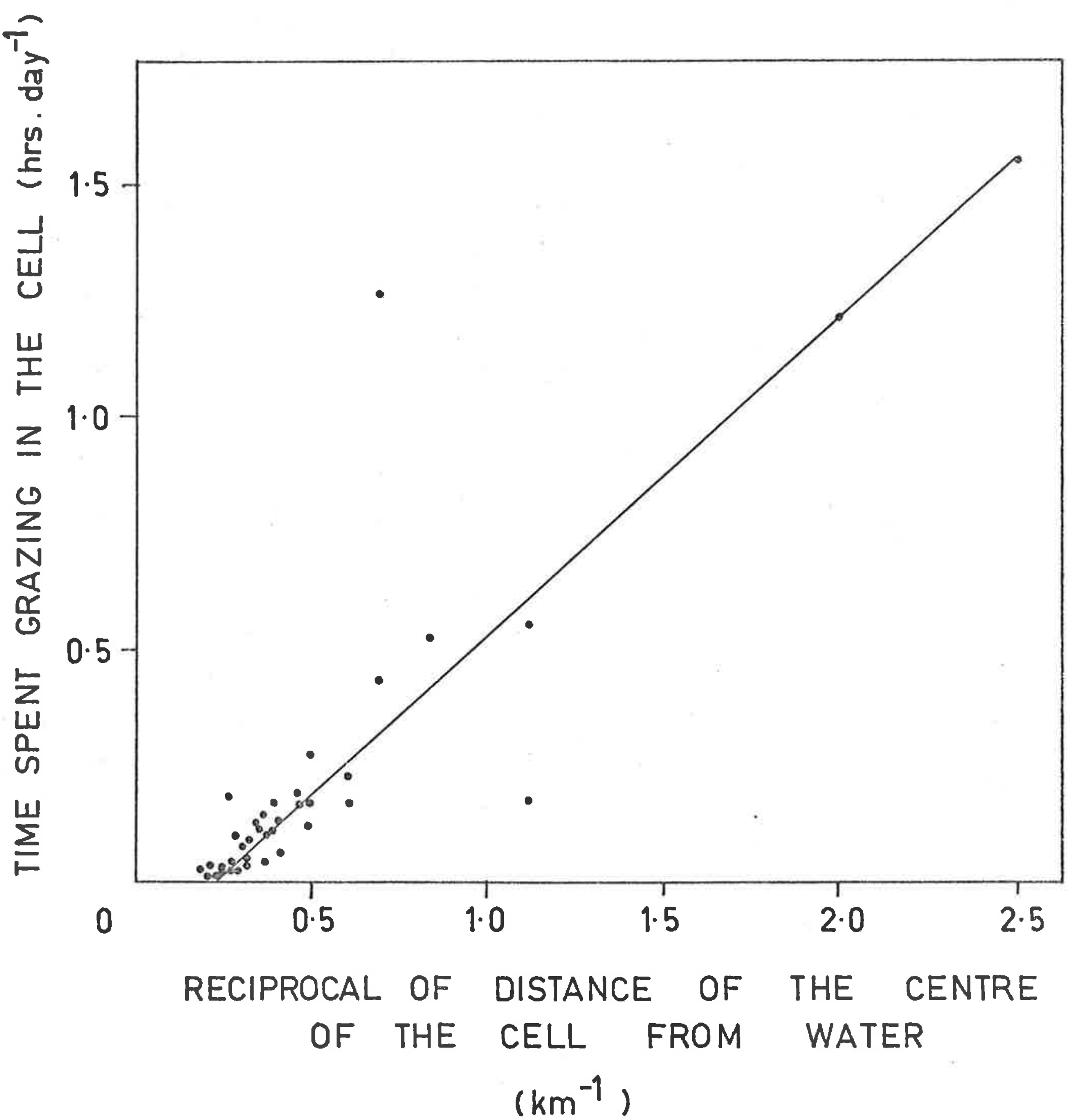


Fig. 11.1. The relationship between simulated grazing time and the distance from water.

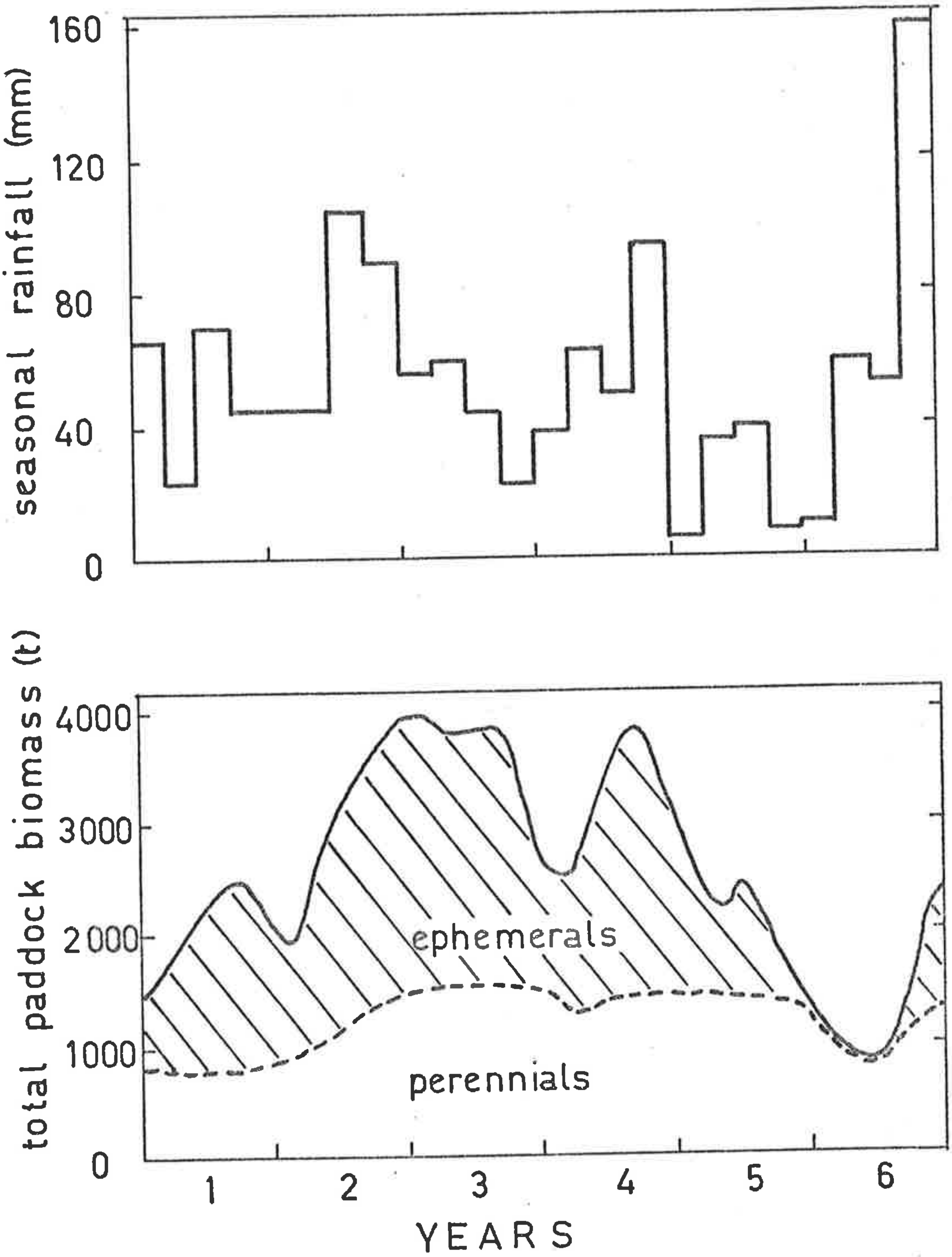


Fig. 11.2. The seasonal rainfall (running autumn, winter, spring, summer in each year) for the standard weather conditions, and the total paddock biomass of ephemerals and perennials in a run with no sheep.

Fig. 11.3 The plotted output from experimental runs, R-1, R-2, R-3, R-7, R-15 and R-18. In the Wertigo maps (pages a & b) the value of the parameter in each cell is represented by the area of the octagons. The scale is indicated by the 3 octagons to the right of the maps. The largest ocatagon represents the variable indicated at the bottom of the map, and the small octagons represent variables x0.5 and x0.1 as large (e.g. in the top left graph of R-1a, the largest octagon represents a biomass of 700 kg and the smaller octagons, 350 kg and 70 kg).

Sheet 'a' maps: The biomass maps on the left hand side of sheet are the final *A. vesicaria* and *K. sedifolia* biomasses in kg ha^{-1}. The 'change' maps are maps of the index described in section 11.1 (p. 239). Deterioration is indicated by solid symbols and improvement by open symbols.

Sheet 'b' maps: The 'total time' is the average time per day that a subflock spends in a particular cell. The grazing time is the hours spent grazing in a particular cell while the extensive time is the time spent in 'extensive activities' (section 8.53) in a particular cell. The 'extensive time' is plotted as the proportion of the total extensive time and is comparable with the results of Lange & Willcocks (fig. 8.19). All of these values are averaged over all the subflocks and over the 6 years of simulation. The total consumption is the consumption of all species by all subflocks over the 6 years.

Sheet 'c' maps: These plots show the course of the simulation. They represent the mean values of each of the parameters over 5 day periods (pentads) except where indicated below. The units on the X axis are months, and January is indicated by the letter J. The Y axes of the other graphs are described below. Where more than two variables are plotted on the same Y axis the second and subsequent plots are numbered 2, 3 etc.

TCONS ... mean total daily consumption (kg hd^{-1} day^{-1})
TE ... mean maximum air temperature ($^{\circ}$C)
RF (2) ... total rainfall in the pentad (cm)
WOOL L. ... wool length at the end of the pentad (m)
(the unlabelled plot is an indicator of cold stress periods)
DRINK ... mean water intake (ml hd^{-1} day^{-1})
WALK ... mean distance walked (km day^{-1})
GRAZ. TIME ... mean grazing time (hr day^{-1})
LIVE WT. ... live weight at the end of the pentad (kg)

T. BIOM ... total paddock biomass at the end of the pentad (tonnes in the paddock)

SM 1 2 3 ... soil moisutre in each of the zones at the end of the pentad (mm)

SL..NIT ... soil nitrogen at the end of the pentad (kg ha^{-1})

Sheet 'd' maps: These are similar to the 'c' maps. The top five maps show the biomasses of each of the taxa at the end of the pentad. The units are tonnes in the paddock (n.b. grass biomasses of over 1000 tonnes are truncated). The lower five graphs show the mean daily consumption per head of each of the taxa (kg hd^{-1} day^{-1})

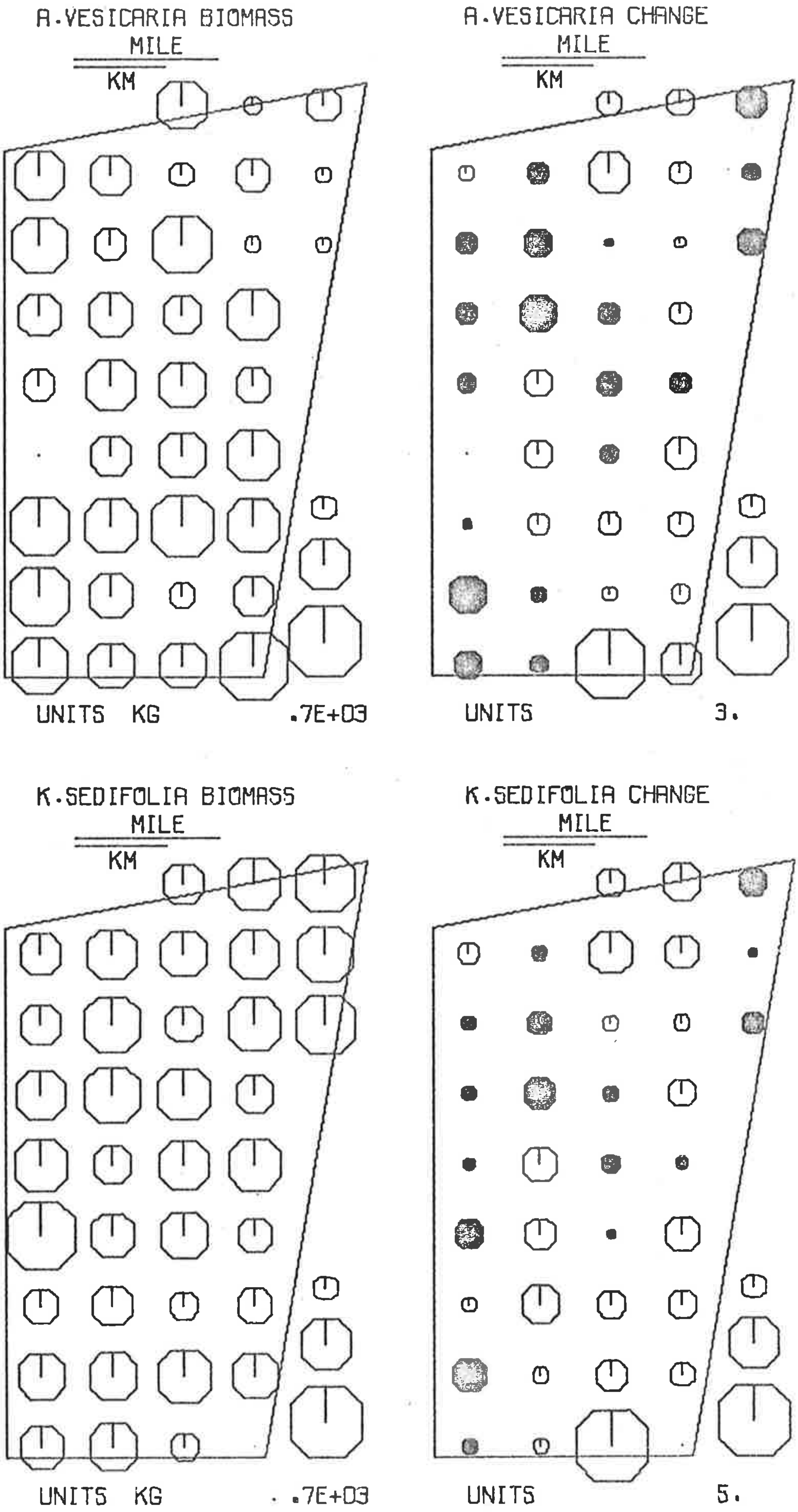

A.VESICARIA BIOMASS
MILE
KM
UNITS KG .7E+03
A.VESICARIA CHANGE
MILE
KM
UNITS 3.
K.SEDIFOLIA BIOMASS
MILE
KM
UNITS KG .7E+03
K.SEDIFOLIA CHANGE
MILE
KM
UNITS 5.

Fig. 11.3. R-1a

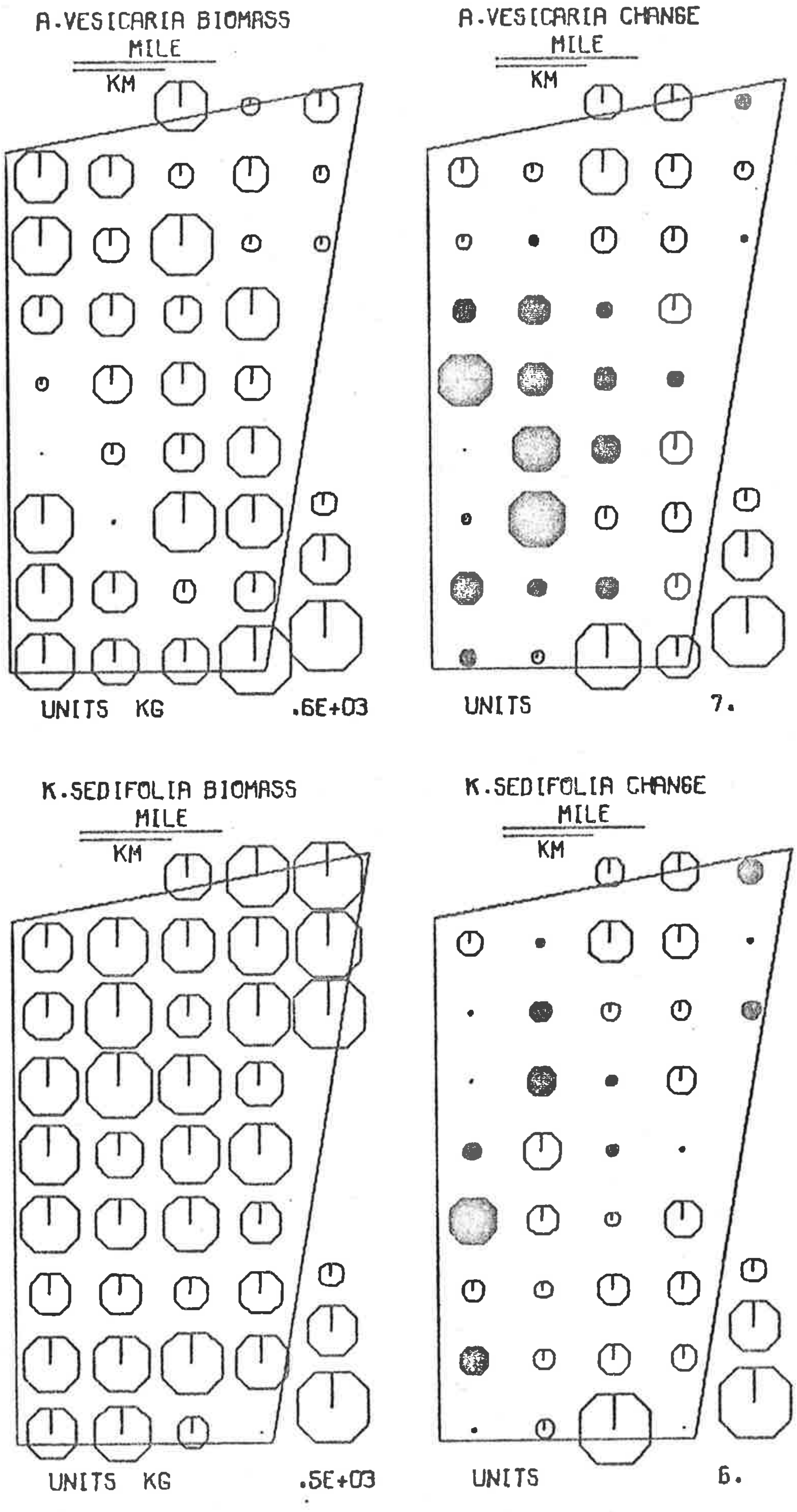

A.VESICARIA BIOMASS
MILE
KM
UNITS KG
.6E+03
A.VESICARIA CHANGE
MILE
KM
UNITS
7.
K.SEDIFOLIA BIOMASS
MILE
KM
UNITS KG
.5E+03
K.SEDIFOLIA CHANGE
MILE
KM
UNITS
6.

Fig. 11.3.

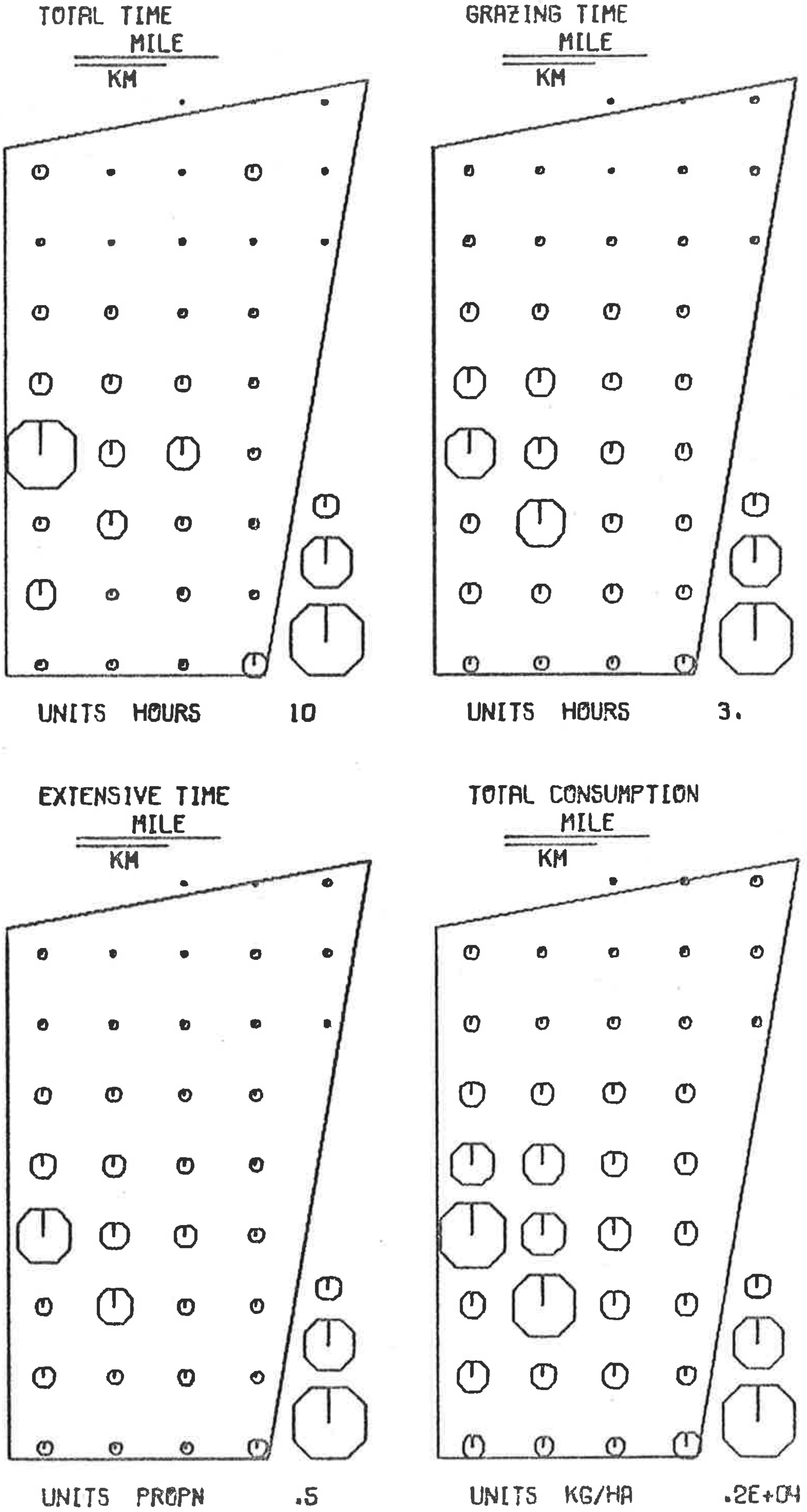

TOTAL TIME
MILE
KM
UNITS HOURS 10
GRAZING TIME
MILE
KM
UNITS HOURS 3.
EXTENSIVE TIME
MILE
KM
UNITS PROPN .5
TOTAL CONSUMPTION
MILE
KM
UNITS KG/HA .2E+04

Fig. 11.3. R-2b

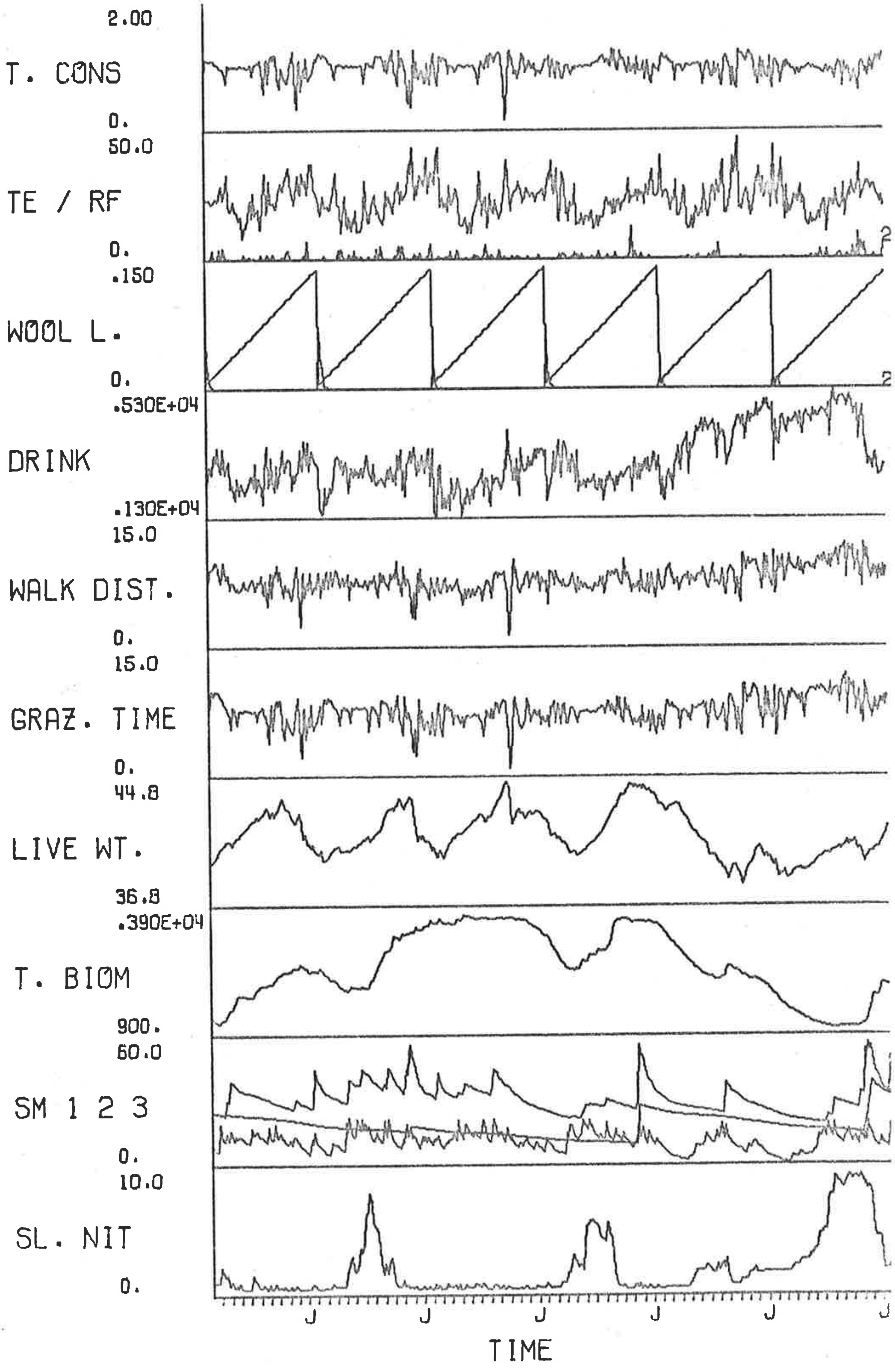

2.00
T. CONS
0.
50.0
TE / RF
0.
2
.150
WOOL L.
0.
2
.530E+04
DRINK
.130E+04
15.0
WALK DIST.
0.
15.0
GRAZ. TIME
0.
44.8
LIVE WT.
36.8
.390E+04
T. BIOM
900.
60.0
SM 1 2 3
0.
10.0
SL. NIT
0.
J
J
J
J
J
J
TIME

Fig. 11.3.

R-2c

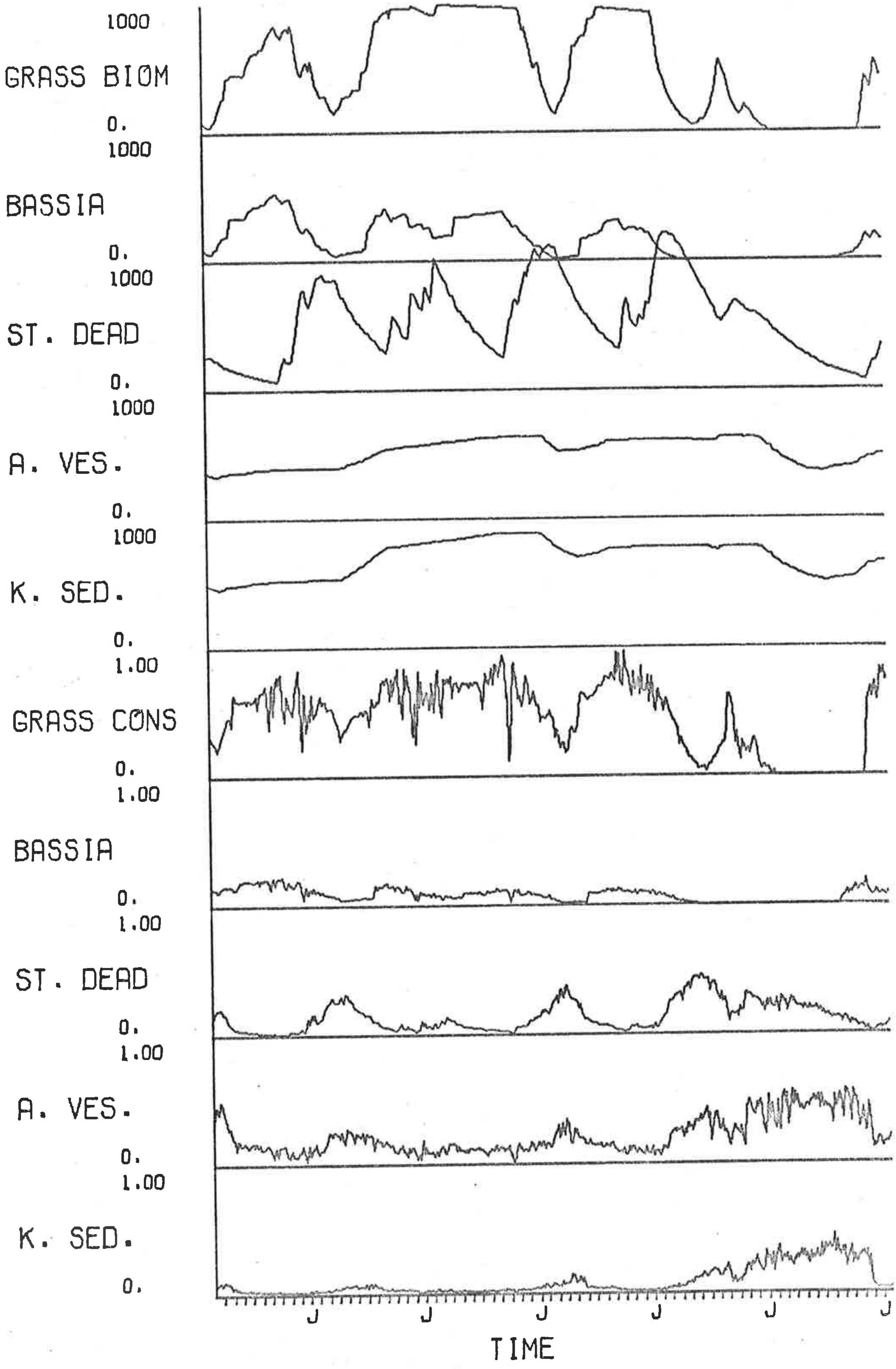
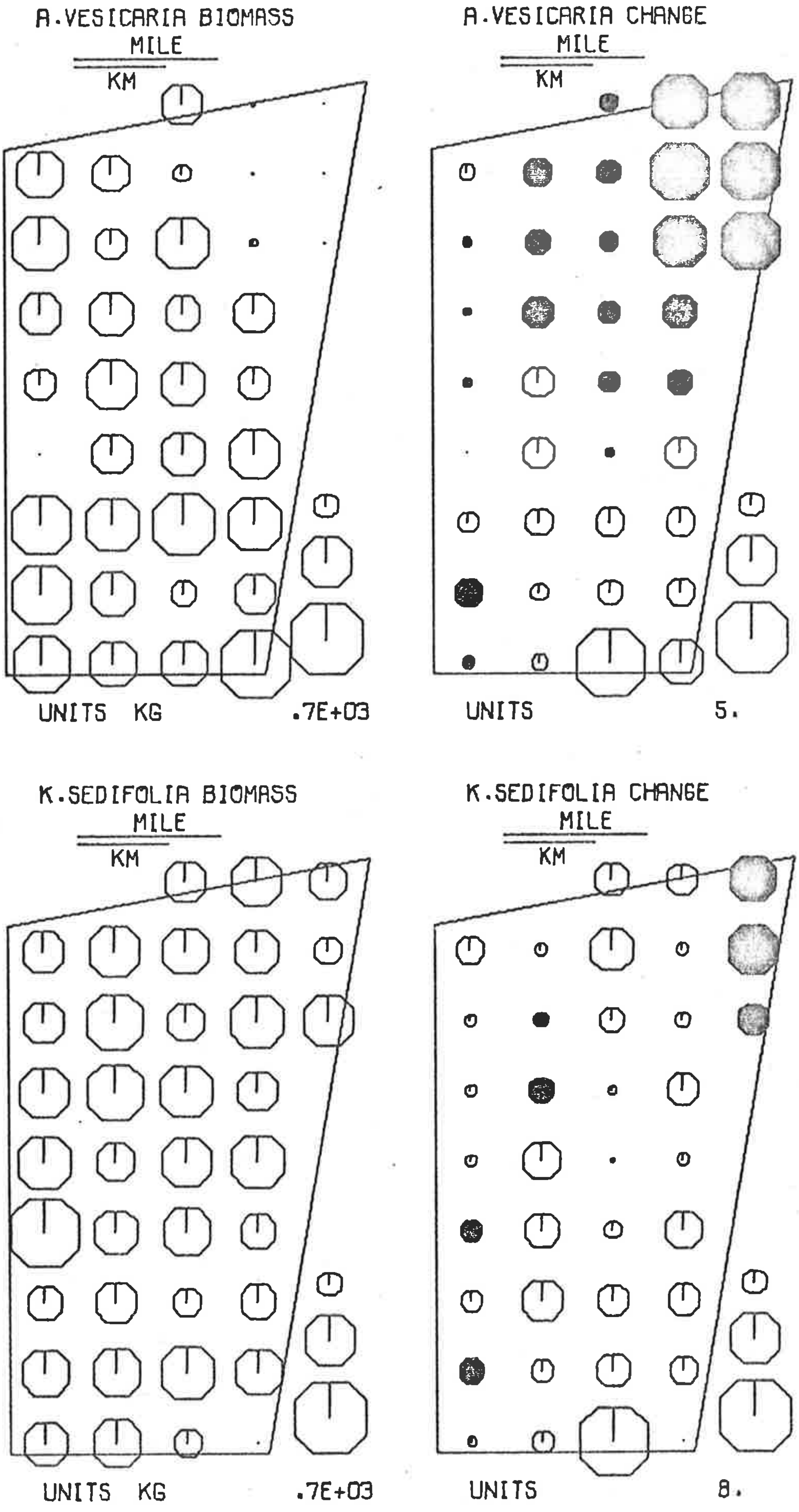

1000
GRASS BIOM
0.
1000
BASSIA
0.
1000
ST. DEAD
0.
1000
A. VES.
0.
1000
K. SED.
0.
1.00
GRASS CONS
0.
1.00
BASSIA
0.
1.00
ST. DEAD
0.
1.00
A. VES.
0.
1.00
K. SED.
0.
J
J
J
J
J
J
TIME

Fig. 11.3

R-2d


A.VESICARIA BIOMASS

A.VESICARIA CHANGE

K.SEDIFOLIA BIOMASS

K.SEDIFOLIA CHANGE

Fig. 11.3

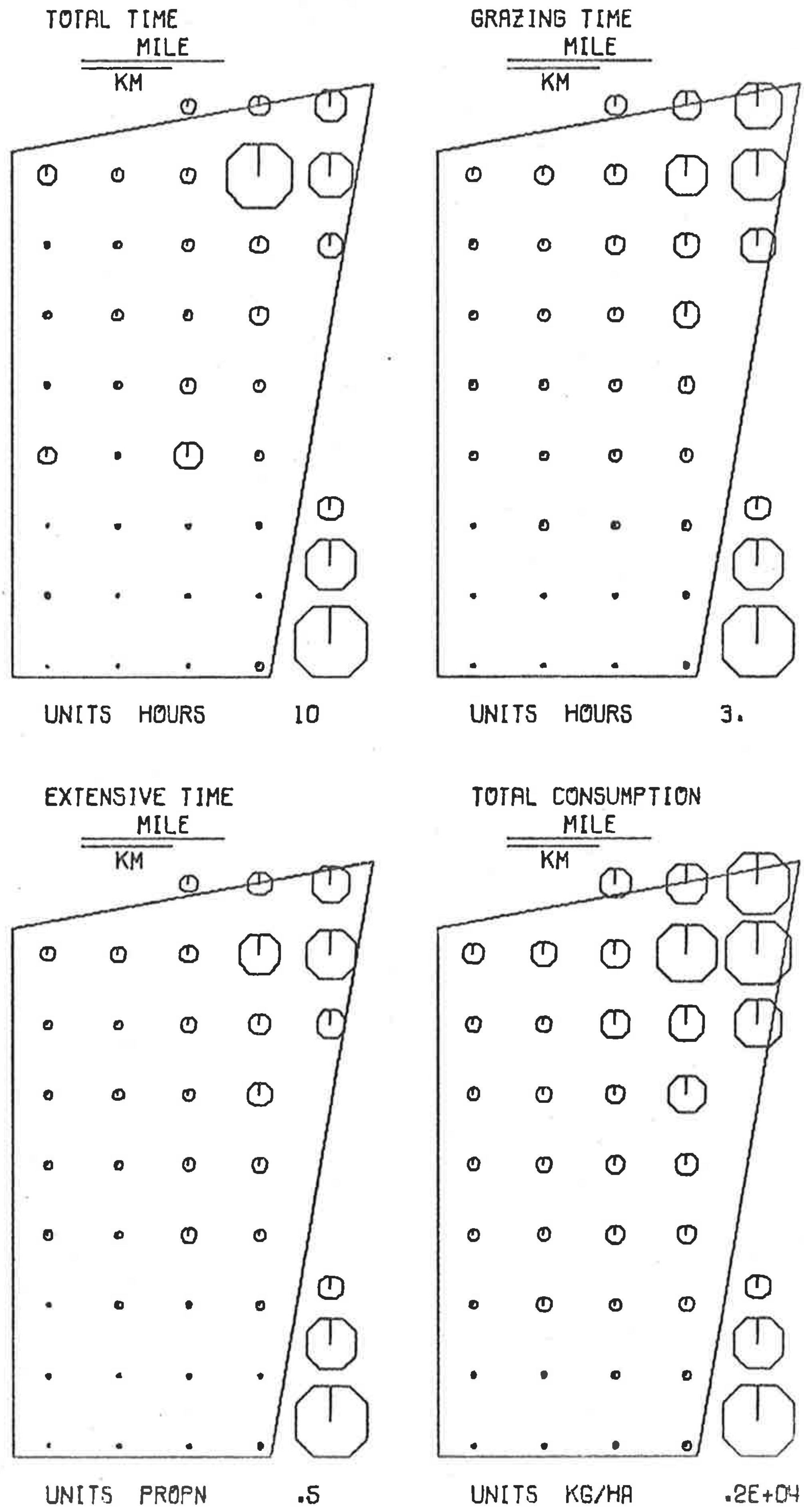
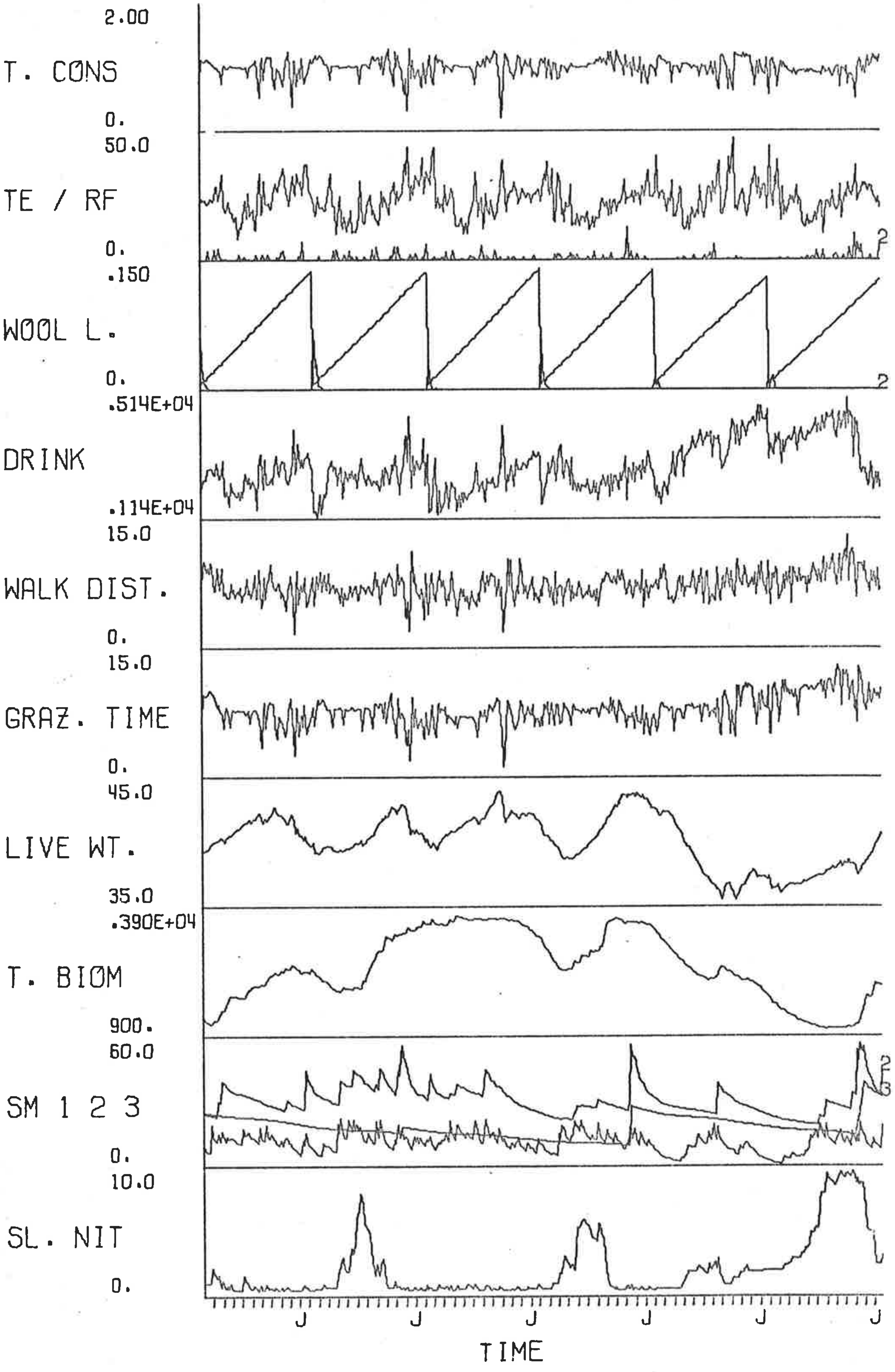

TOTAL TIME
MILE
KM
UNITS HOURS 10
GRAZING TIME
MILE
KM
UNITS HOURS 3.
EXTENSIVE TIME
MILE
KM
UNITS PROPN .5
TOTAL CONSUMPTION
MILE
KM
UNITS KG/HA .2E+04

Fig. 11.3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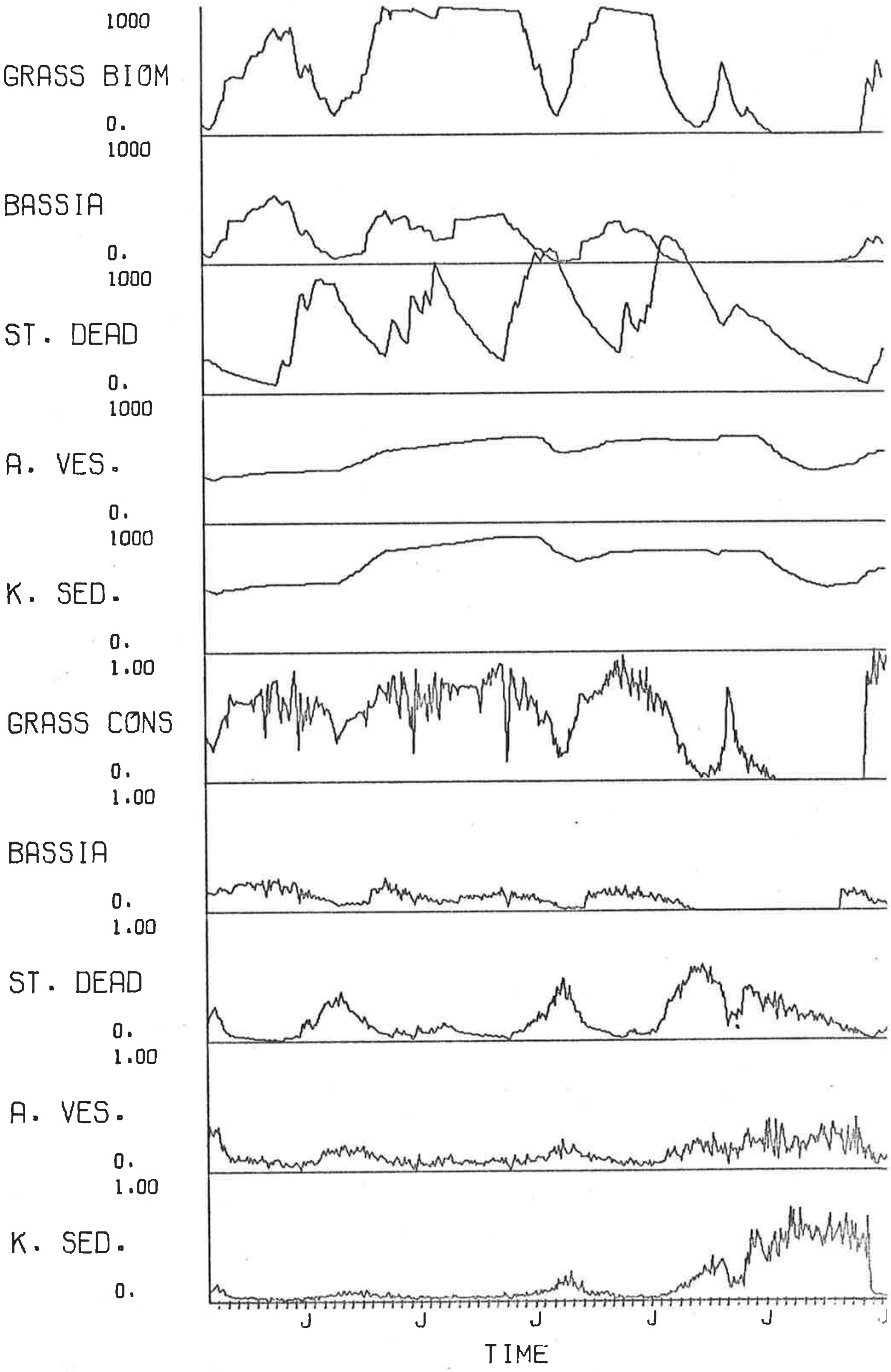
0.
50.0
TE / RF
0.
2
.150
WOOL L.
0.
2
.514E+04
DRINK
.114E+04
15.0
WALK DIST.
0.
15.0
GRAZ. TIME
0.
45.0
LIVE WT.
35.0
.390E+04
T. BIOM
900.
60.0
SM 1 2 3
2
3
0.
10.0
SL. NIT
0.
J
J
J
J
J
J
TIME

Fig. 11.3. R-3c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BASSIA
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1000
ST. DEAD
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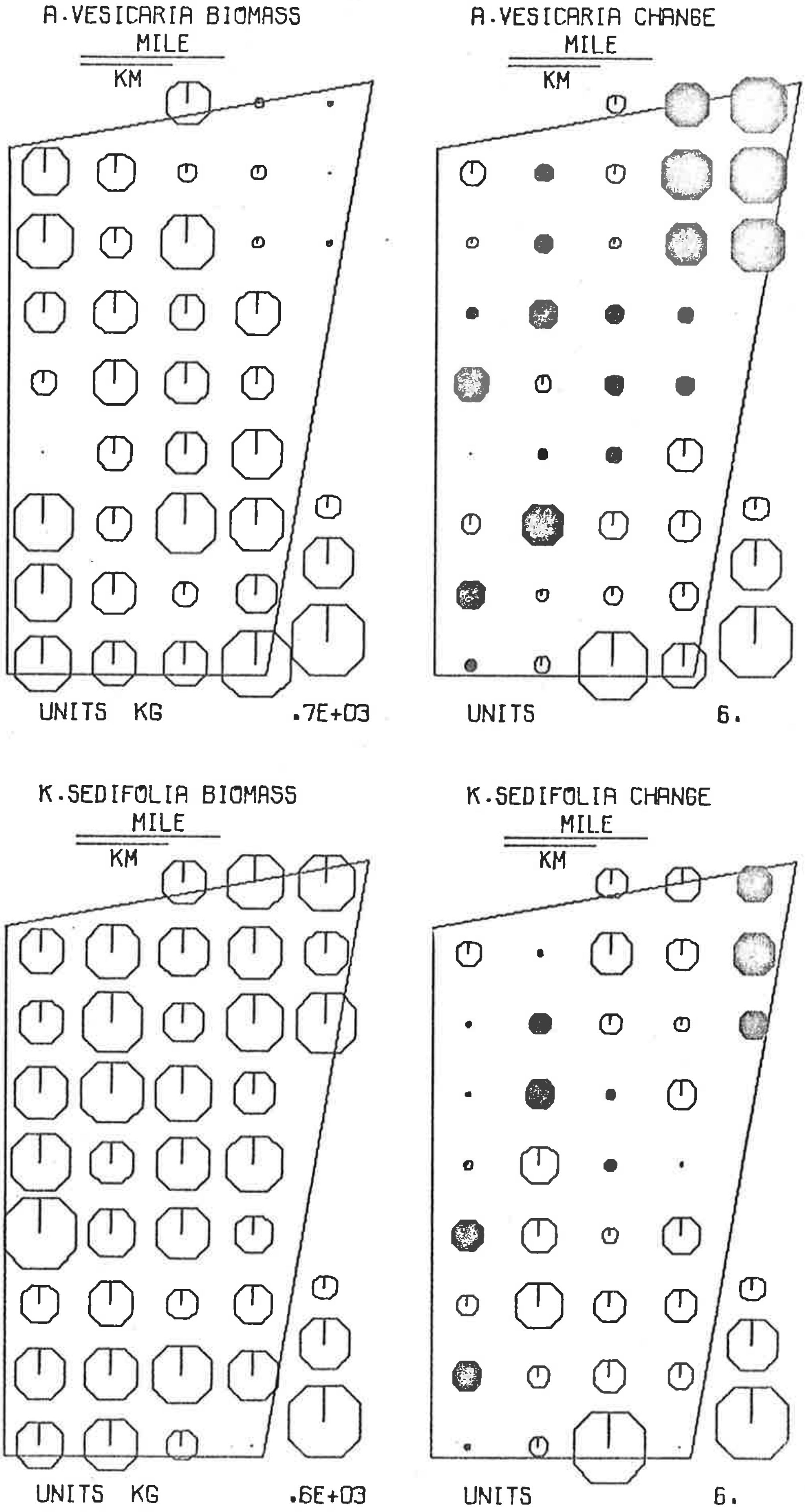
1000
A. VES.
0.
1000
K. SED.
0.
1.00
GRASS CONS
0.
1.00
BASSIA
0.
1.00
ST. DEAD
0.
1.00
A. VES.
0.
1.00
K. SED.
0.
J
J
J
J
J
J
TIME

Fig. 11.3.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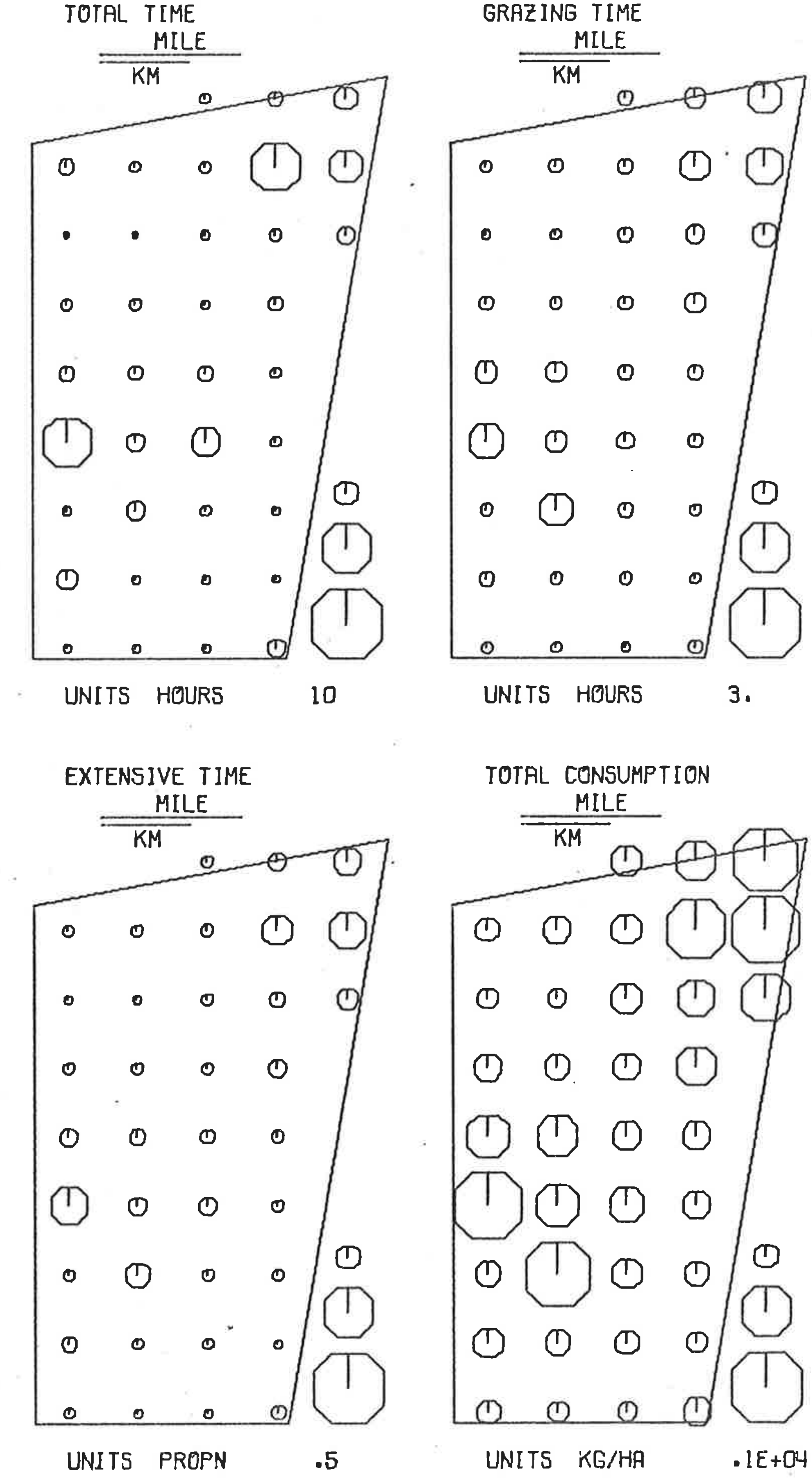
MILE
KM
UNITS KG
.7E+03
A.VESICARIA CHANGE
MILE
KM
UNITS
6.
K.SEDIFOLIA BIOMASS
MILE
KM
UNITS KG
.6E+03
K.SEDIFOLIA CHANGE
MILE
KM
UNITS
6.

Fig. 11.3.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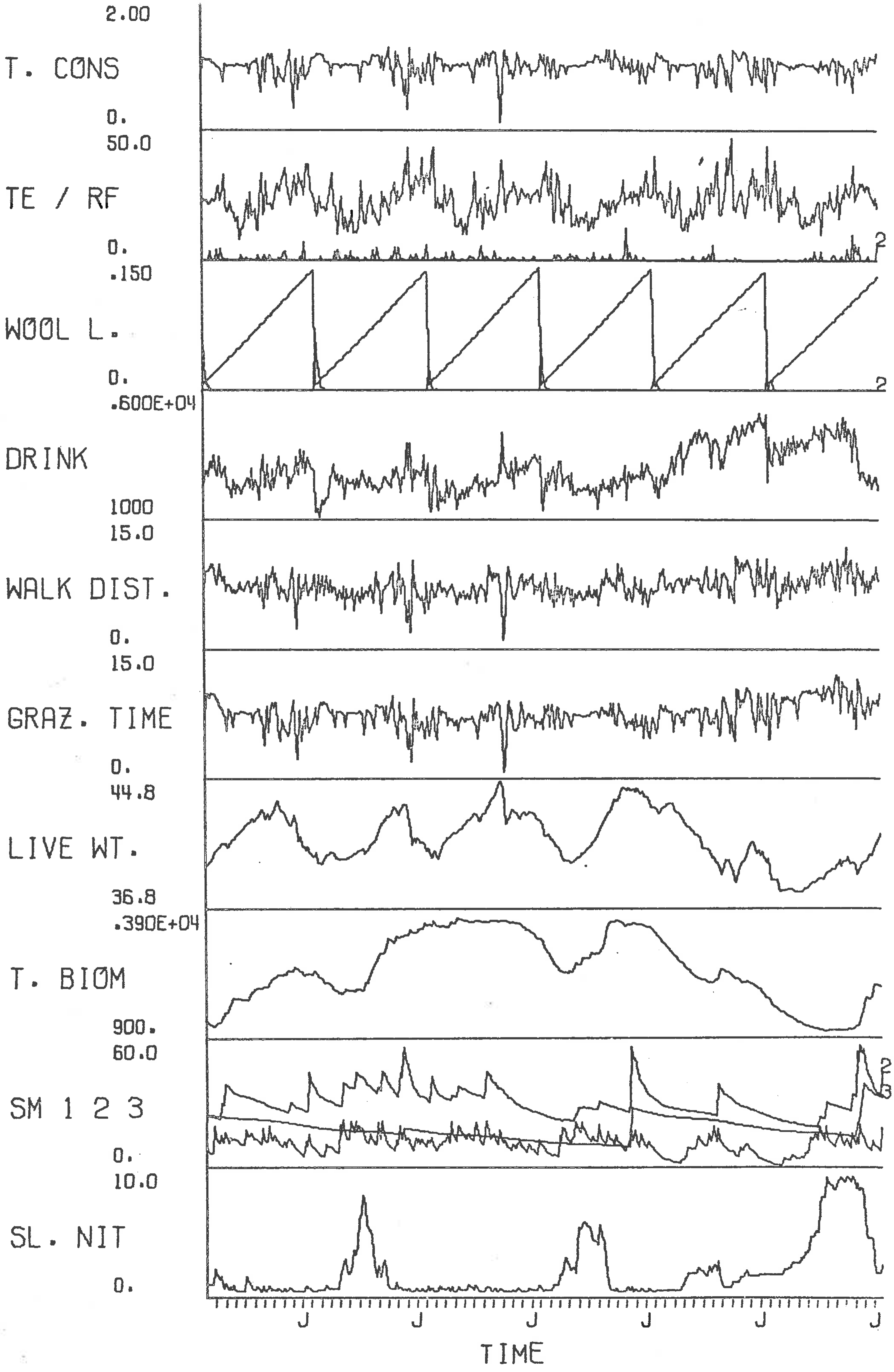
MILE
KM
UNITS HOURS 10
GRAZING TIME
MILE
KM
UNITS HOURS 3.
EXTENSIVE TIME
MILE
KM
UNITS PROPN .5
TOTAL CONSUMPTION
MILE
KM
UNITS KG/HA .1E+04

Fig. 11.3. R-7b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50.0
TE / RF
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2
.150
WOOL L.
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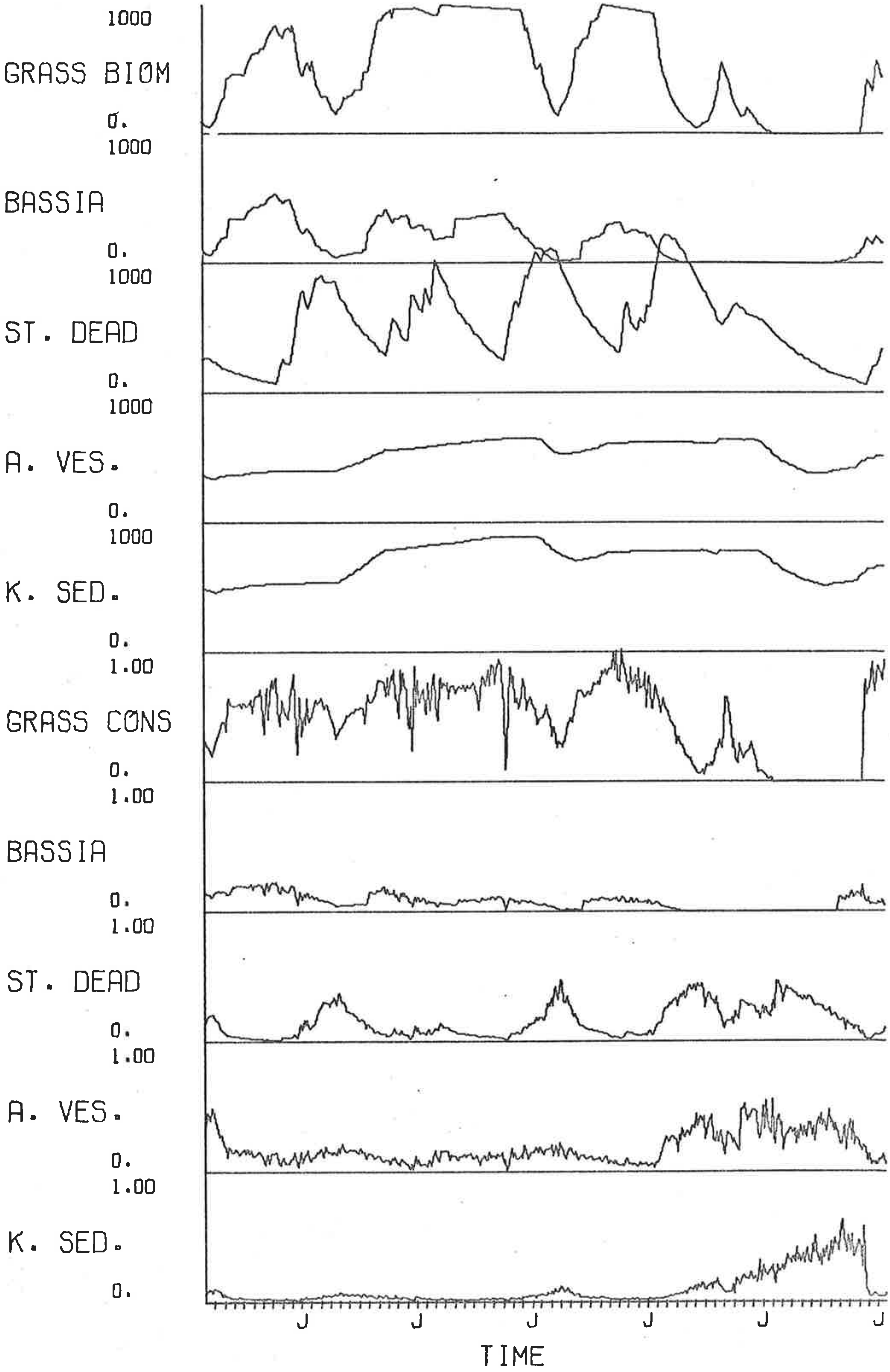
2
.600E+04
DRINK
1000
15.0
WALK DIST.
0.
15.0
GRAZ. TIME
0.
44.8
LIVE WT.
36.8
.390E+04
T. BIOM
900.
60.0
SM 1 2 3
0.
2
3
10.0
SL. NIT
0.
J
J
J
J
J
J
TIME

Fig. 11.3. R-7c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1000
BASSIA
0.
1000
ST. DEAD
0.
1000
A. VES.
0.
1000
K. SED.
0.
1.00
GRASS CONS
0.
1.00
BASSIA
0.
1.00
ST. DEAD
0.
1.00
A. VES.
0.
1.00
K. SED.
0.
J
J
J
J
J
J
TIME

Fig. 11.3.

R-7d

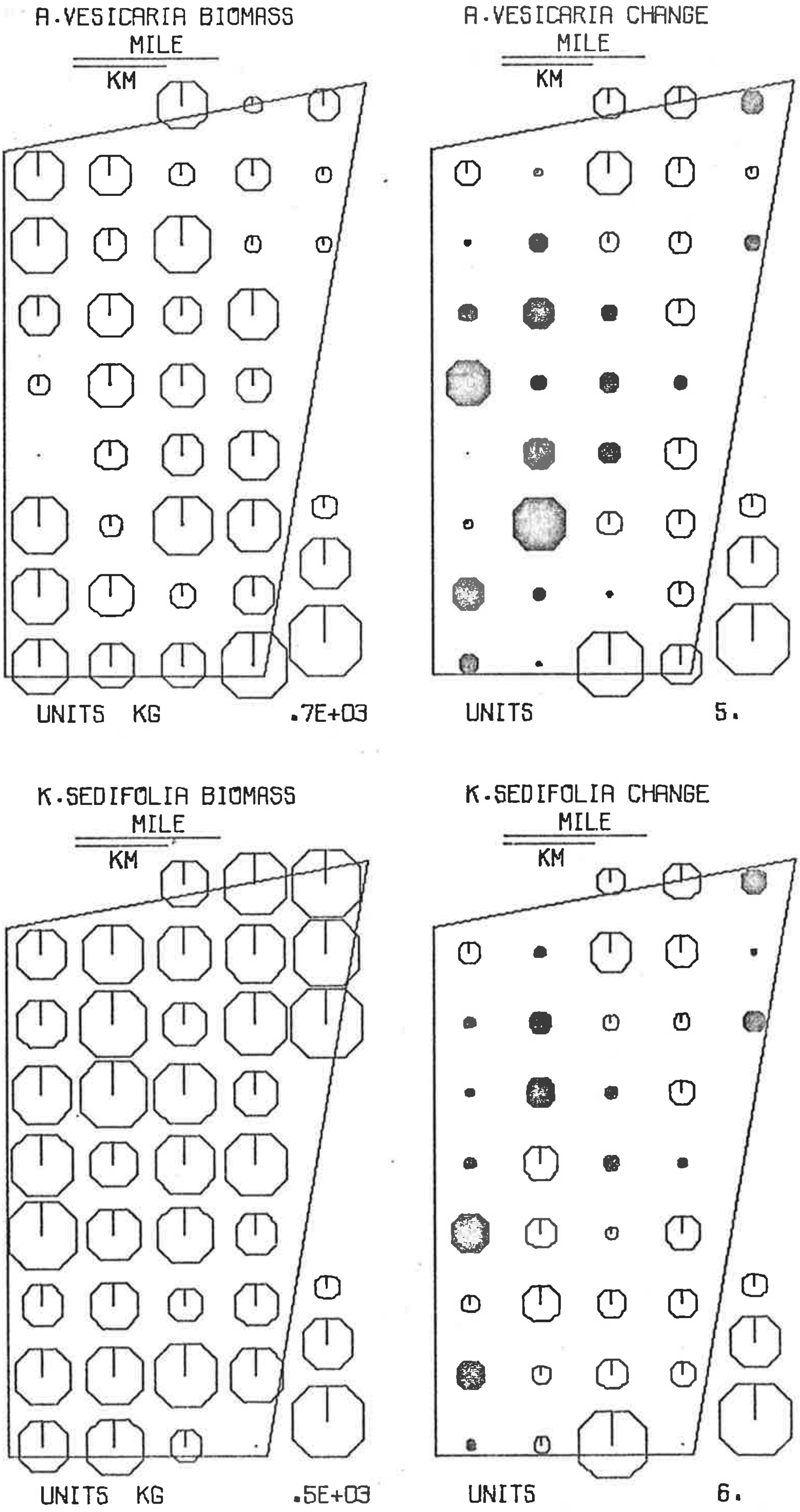
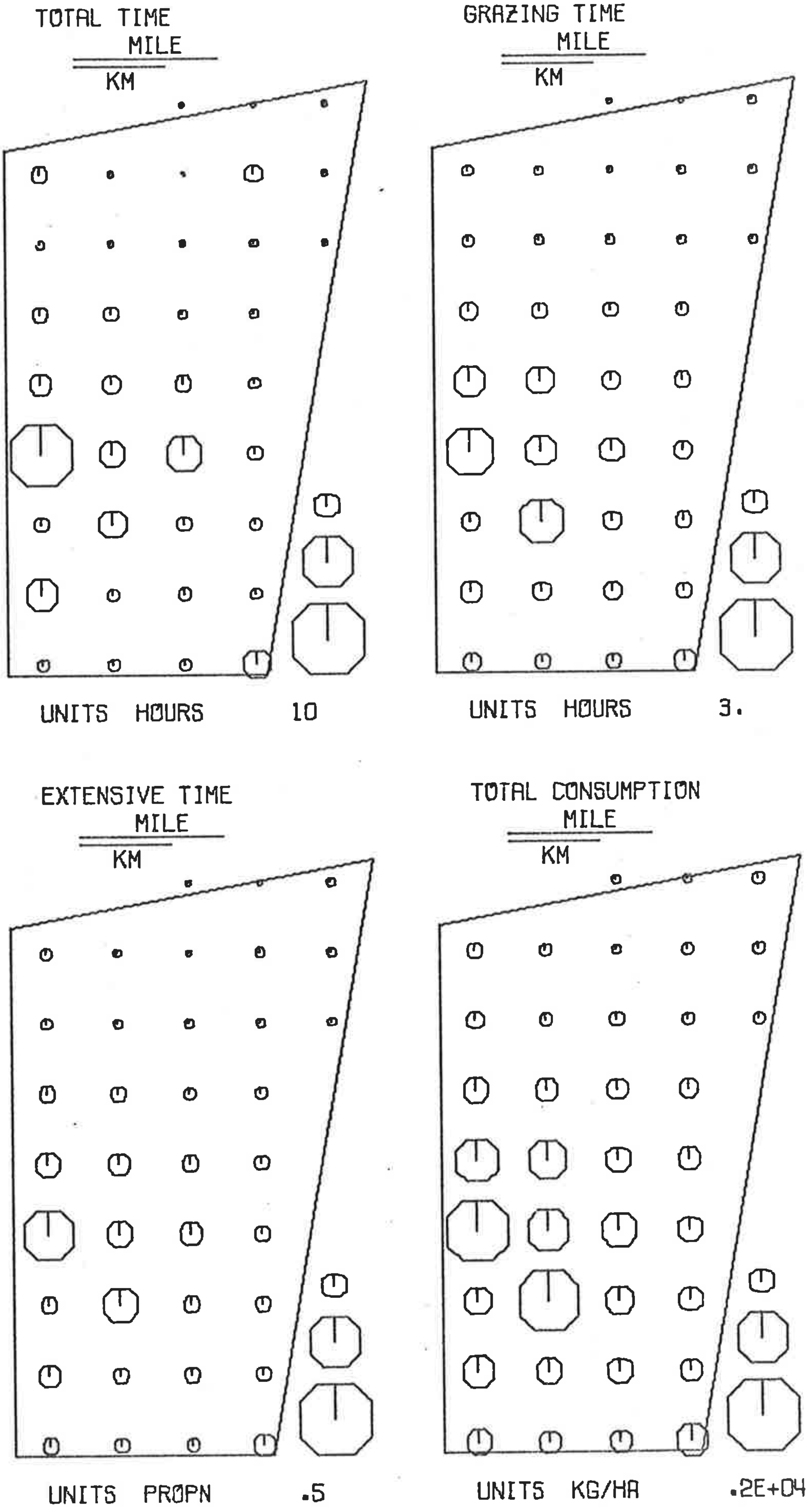

A.VESICARIA BIOMASS
MILE
KM
UNITS KG
.7E+03
A.VESICARIA CHANGE
MILE
KM
UNITS
5.
K.SEDIFOLIA BIOMASS
MILE
KM
UNITS KG
.5E+03
K.SEDIFOLIA CHANGE
MILE
KM
UNITS
6.

Fig. 11.3.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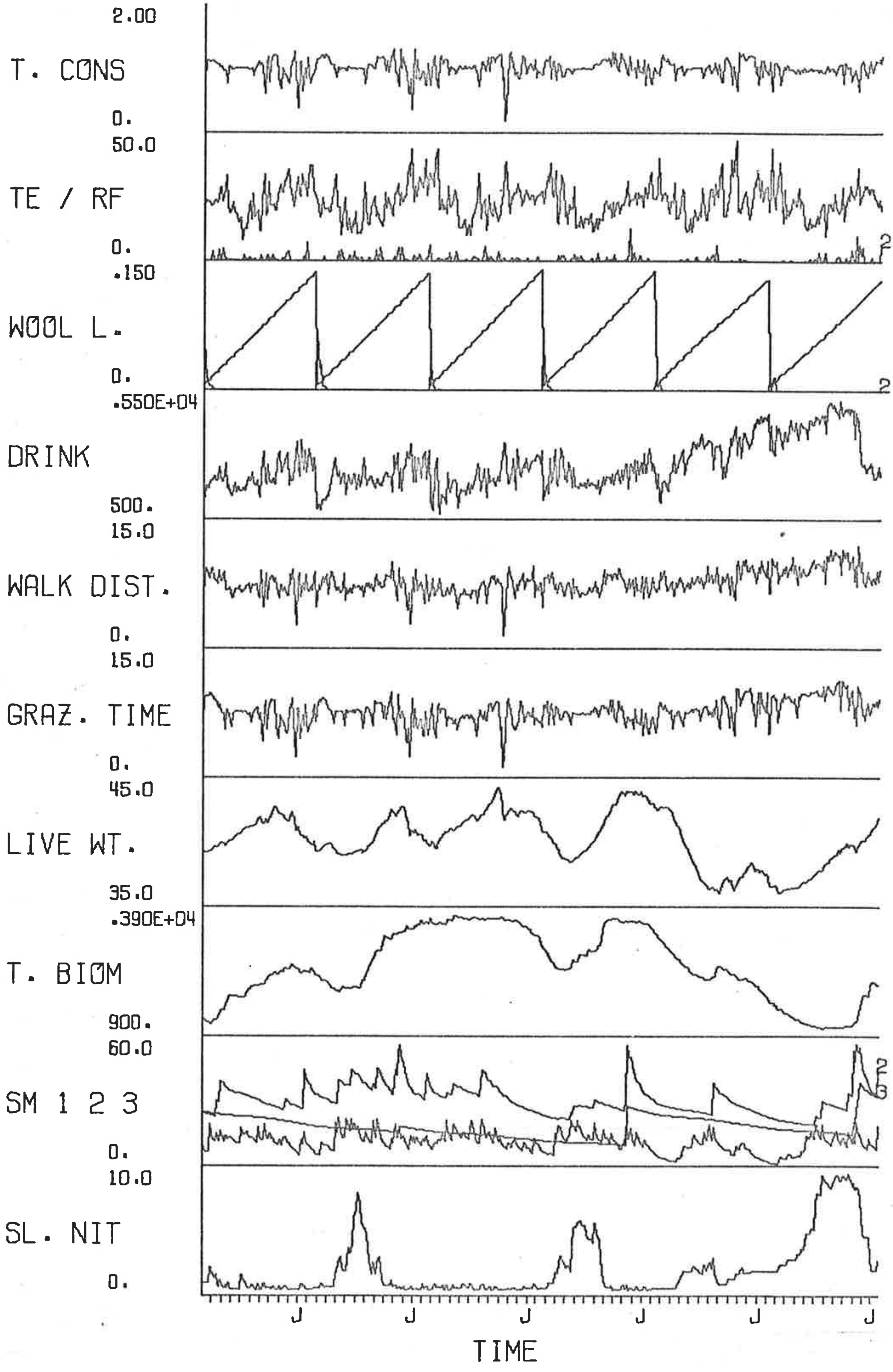
MILE
KM
UNITS HOURS 10
GRAZING TIME
MILE
KM
UNITS HOURS 3.
EXTENSIVE TIME
MILE
KM
UNITS PROPN .5
TOTAL CONSUMPTION
MILE
KM
UNITS KG/HA .2E+04

Fig. 11.3.


2.00
T. CONS
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50.0
TE / RF
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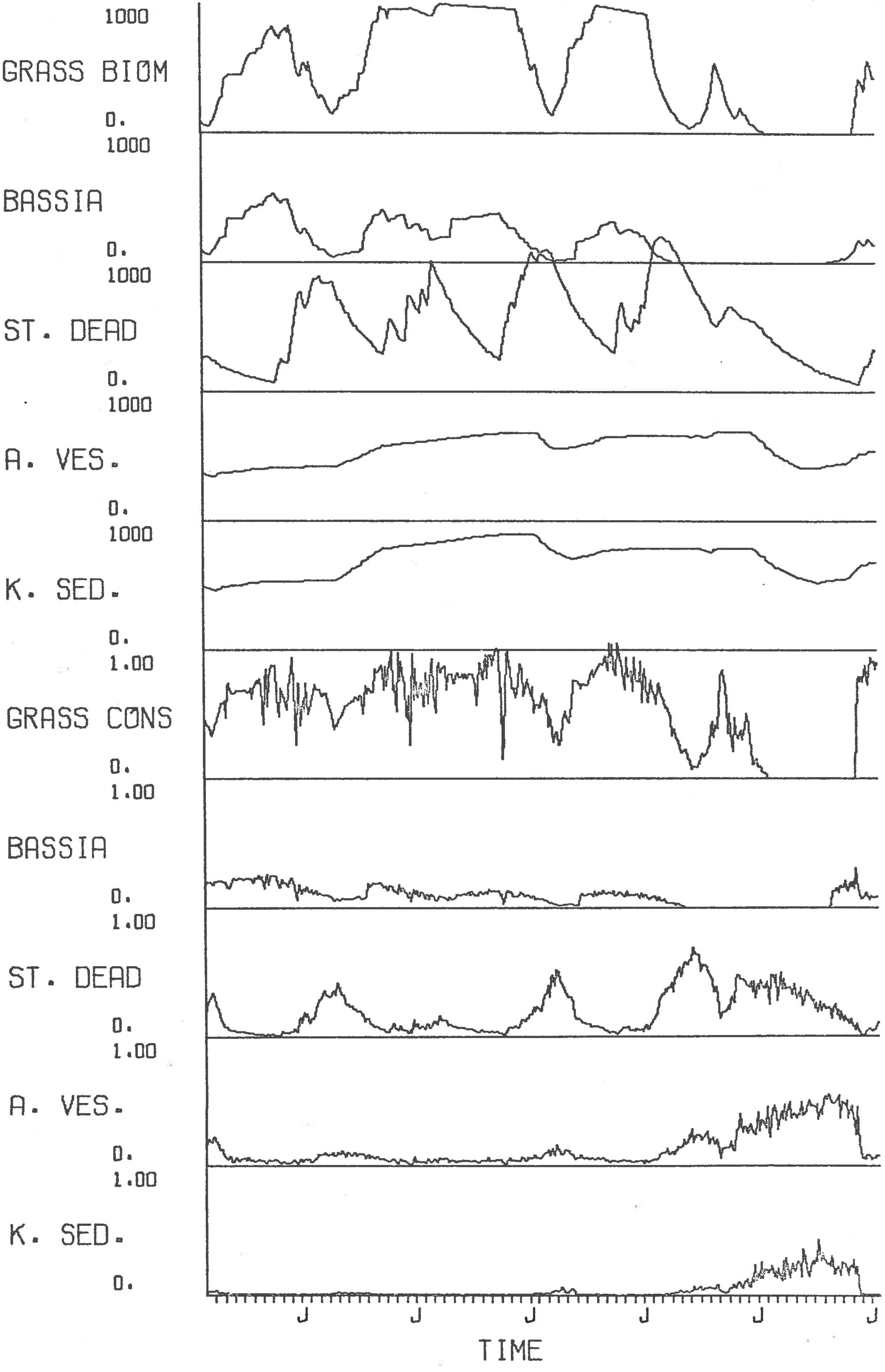
2
.150
WOOL L.
0.
2
.550E+04
DRINK
500.
15.0
WALK DIST.
0.
15.0
GRAZ. TIME
0.
45.0
LIVE WT.
35.0
.390E+04
T. BIOM
900.
60.0
SM 1 2 3
2
3
0.
10.0
SL. NIT
0.
J
J
J
J
J
J
TIME

Fig. 11.3.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0.
1000
BASSIA
0.
1000
ST. DEAD
0.
1000
A. VES.
0.
1000
K. SED.
0.
1.00
GRASS CØNS
0.
1.00
BASSIA
0.
1.00
ST. DEAD
0.
1.00
A. VES.
0.
1.00
K. SED.
0.
J
J
J
J
J
J
TIME

Fig. 11.3.

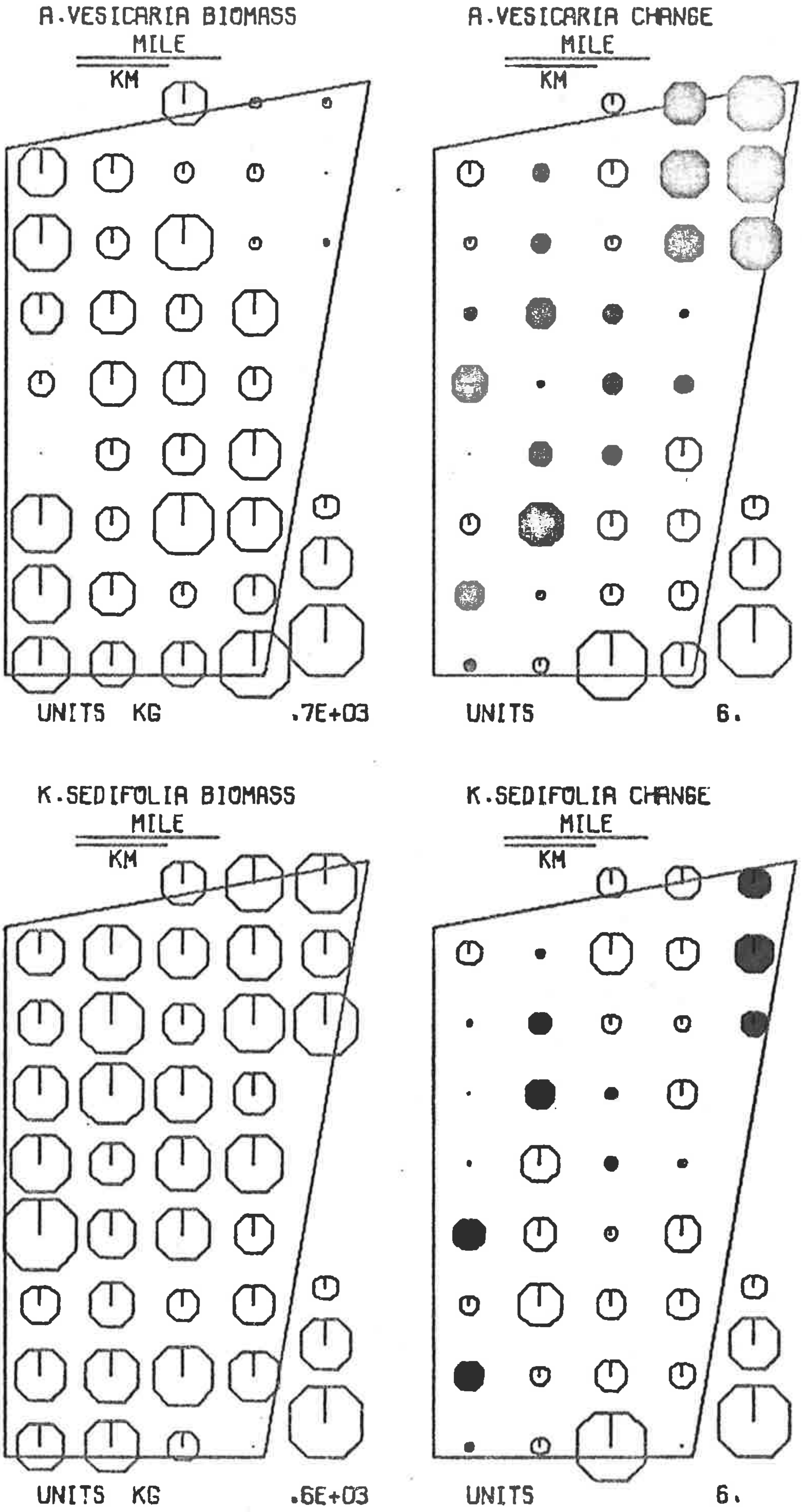

A.VESICARIA BIOMASS
MILE
KM
UNITS KG
.7E+03
A.VESICARIA CHANGE
MILE
KM
UNITS
6.
K.SEDIFOLIA BIOMASS
MILE
KM
UNITS KG
.6E+03
K.SEDIFOLIA CHANGE
MILE
KM
UNITS
6.

Fig. 11.3.

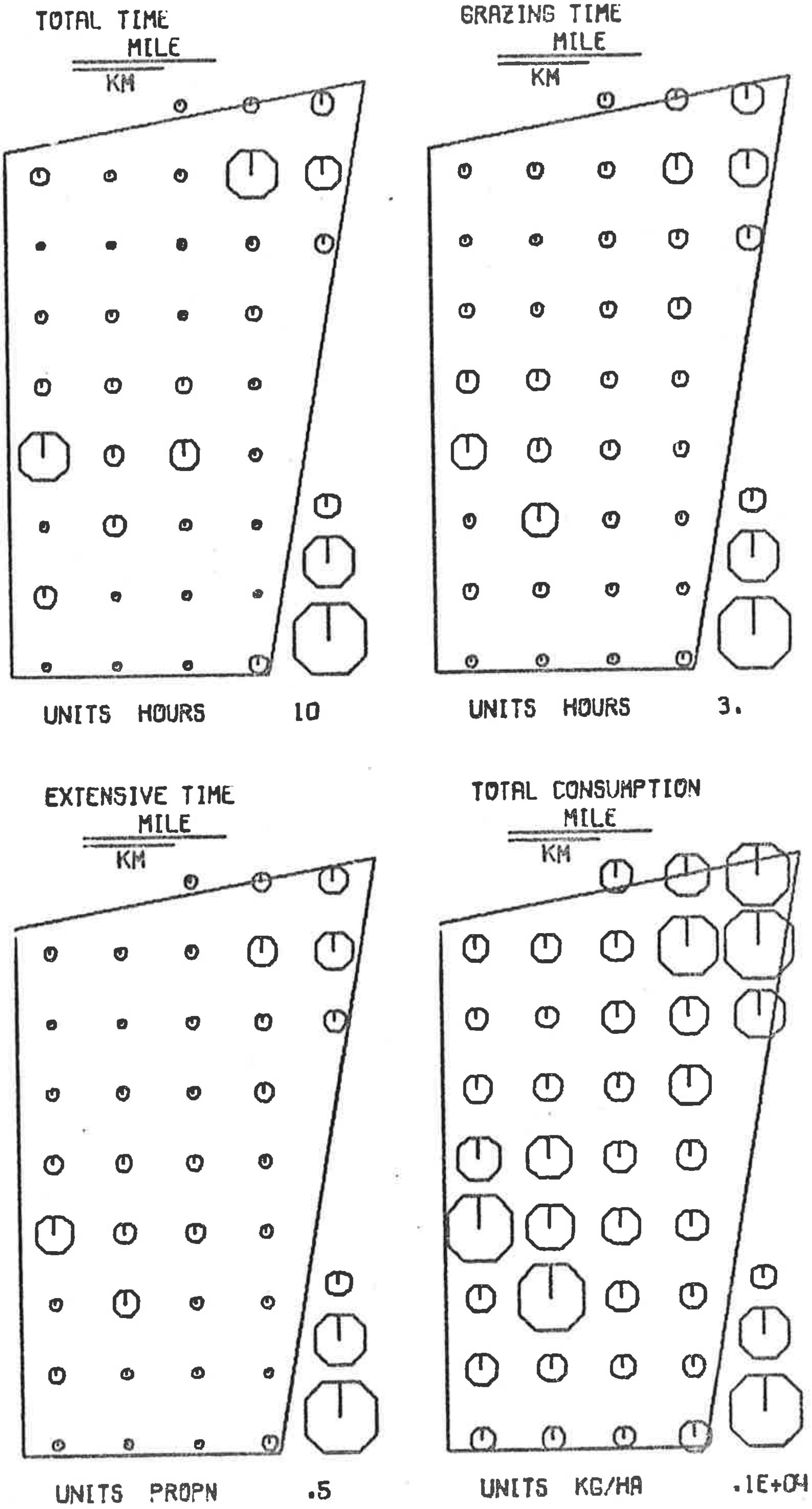
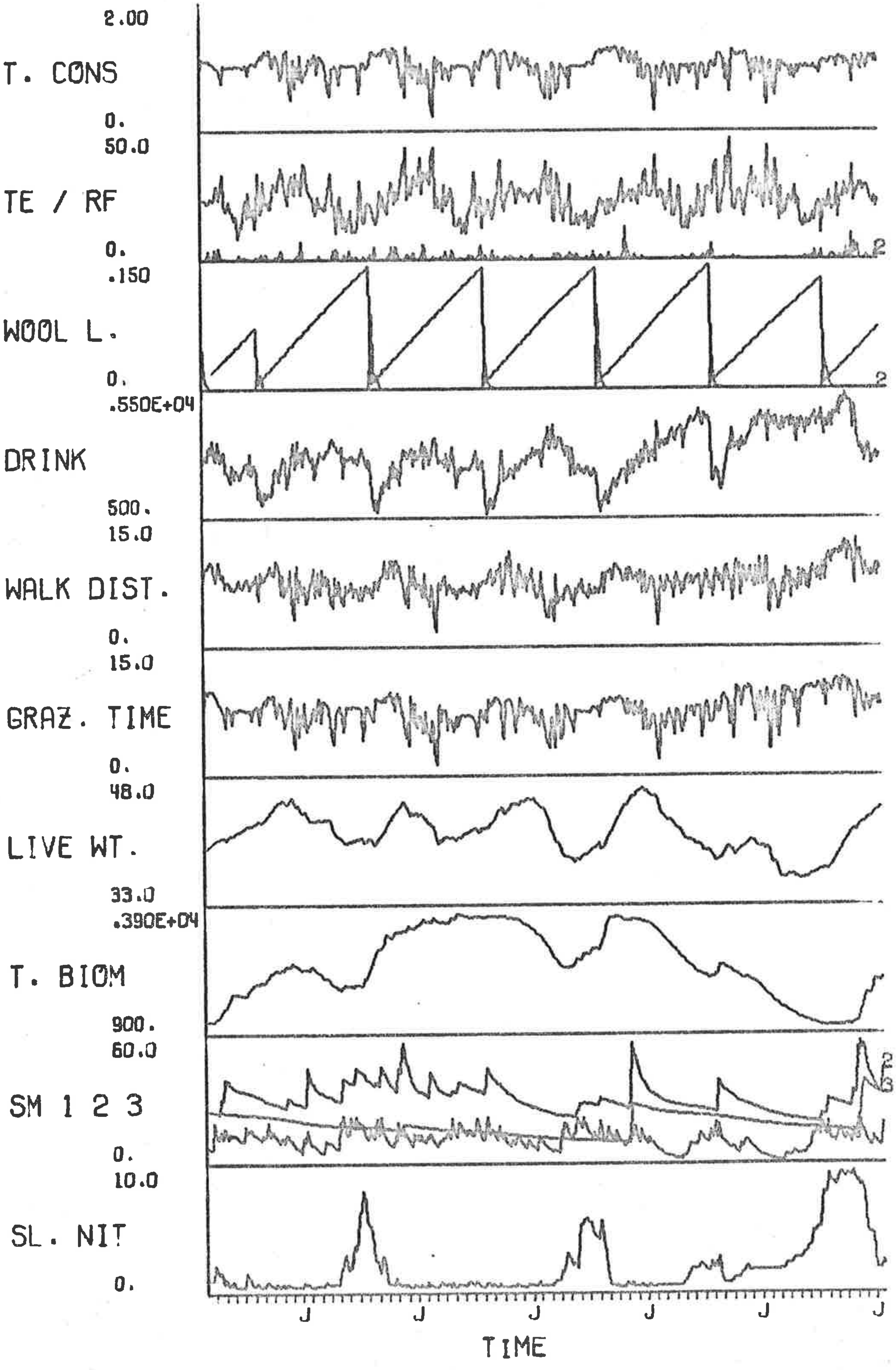

TOTAL TIME
MILE
KM
UNITS HOURS 10
GRAZING TIME
MILE
KM
UNITS HOURS 3.
EXTENSIVE TIME
MILE
KM
UNITS PROPN .5
TOTAL CONSUMPTION
MILE
KM
UNITS KG/HA .1E+04

Fig. 11.3. R-18b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50.0
TE / RF
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2
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WOOL L.
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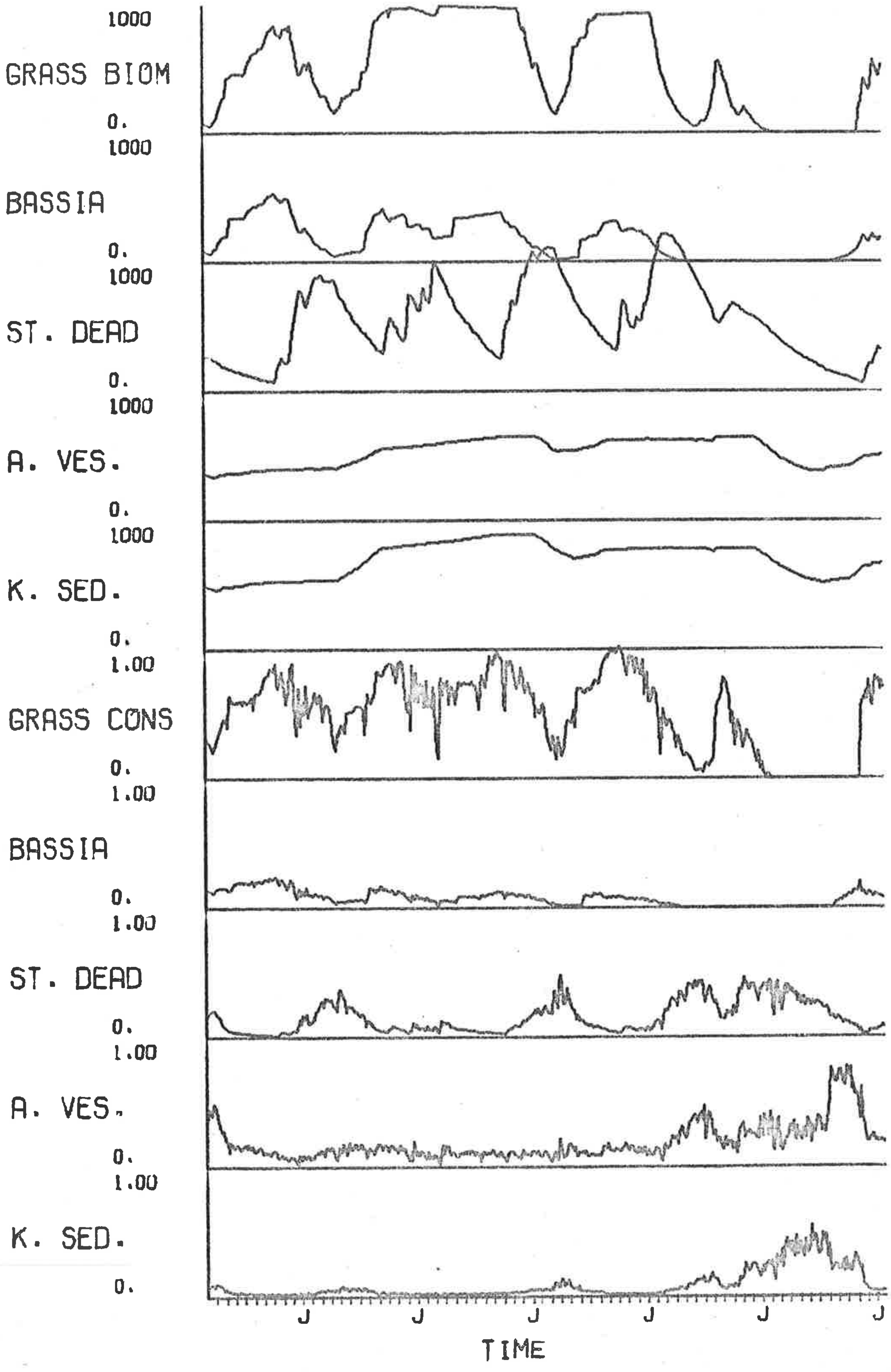
2
.550E+04
DRINK
500.
15.0
WALK DIST.
0.
15.0
GRAZ. TIME
0.
48.0
LIVE WT.
33.0
.390E+04
T. BIOM
900.
60.0
SM 1 2 3
2
3
0.
10.0
SL. NIT
0.
J
J
J
J
J
J
TIME

Fig. 11.3. R-18c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1000
BASSIA
0.
1000
ST. DEAD
0.
1000
A. VES.
0.
1000
K. SED.
0.
1.00
GRASS CONS
0.
1.00
BASSIA
0.
1.00
ST. DEAD
0.
1.00
A. VES.
0.
1.00
K. SED.
0.
J
J
J
J
J
J
TIME

Fig. 11.3.

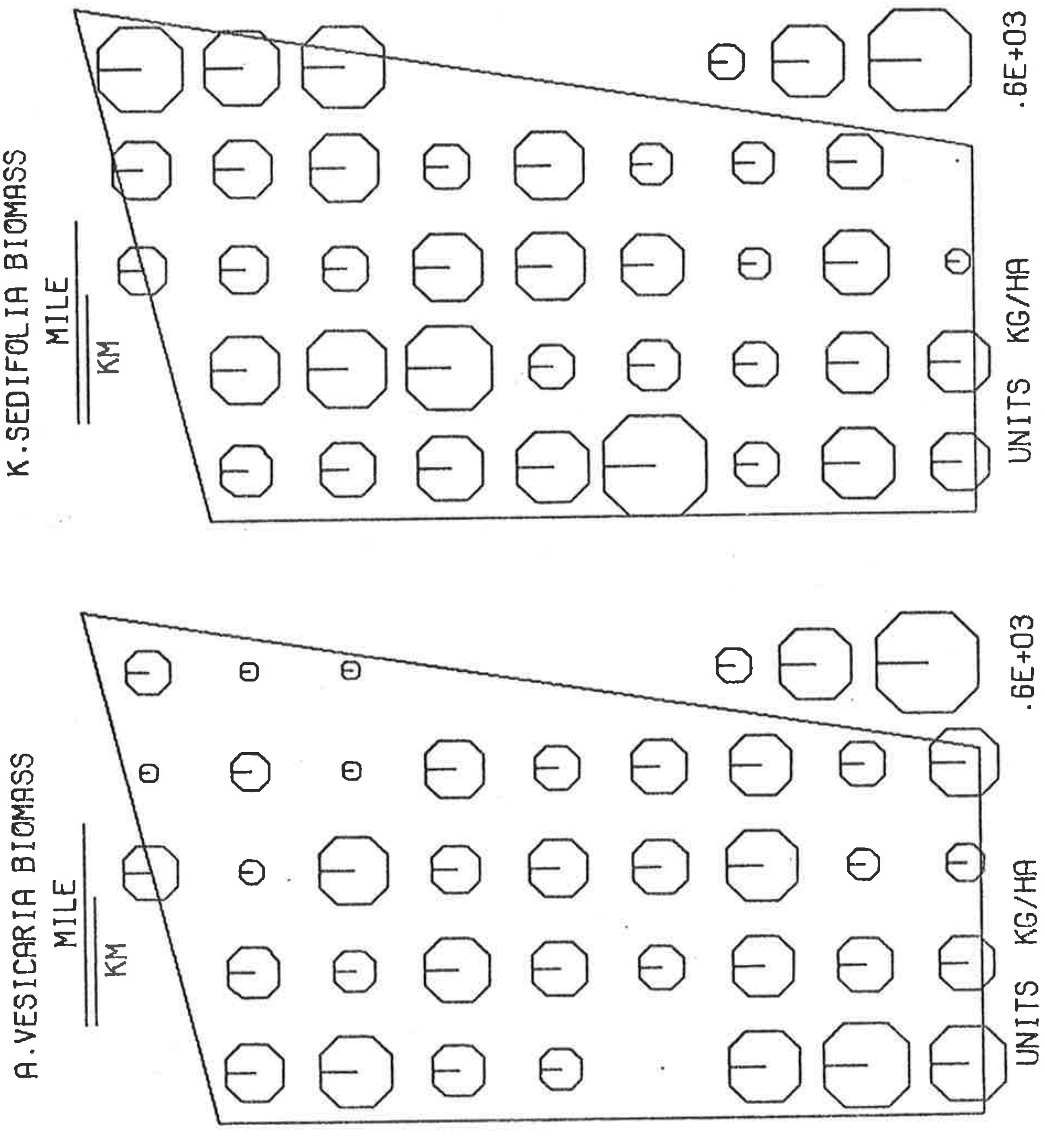


Fig. 11.4. The initial perennial biomasses used in all runs of the model. These data are based on biomass estimates made in October 1972.

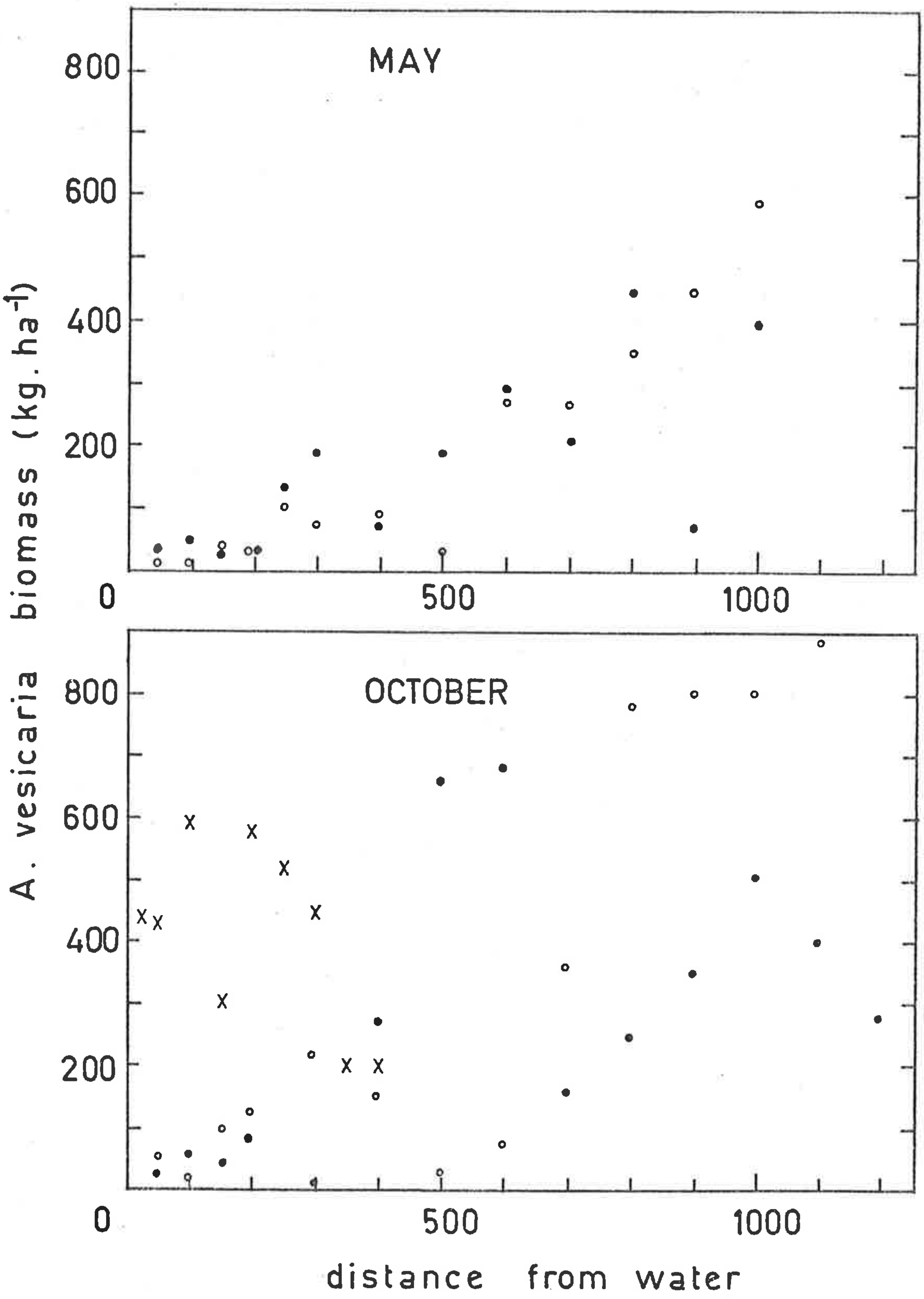


Fig. 11.5a. Biomass of *A. vesicaria* along transects from the trough water-point. The transects with the azimuths 335° (●) and 360° (o) are within the paddock and subject to heavy grazing, while the transect with the azimuth 40° (x) is very lightly grazed (this transect terminated in a water course).

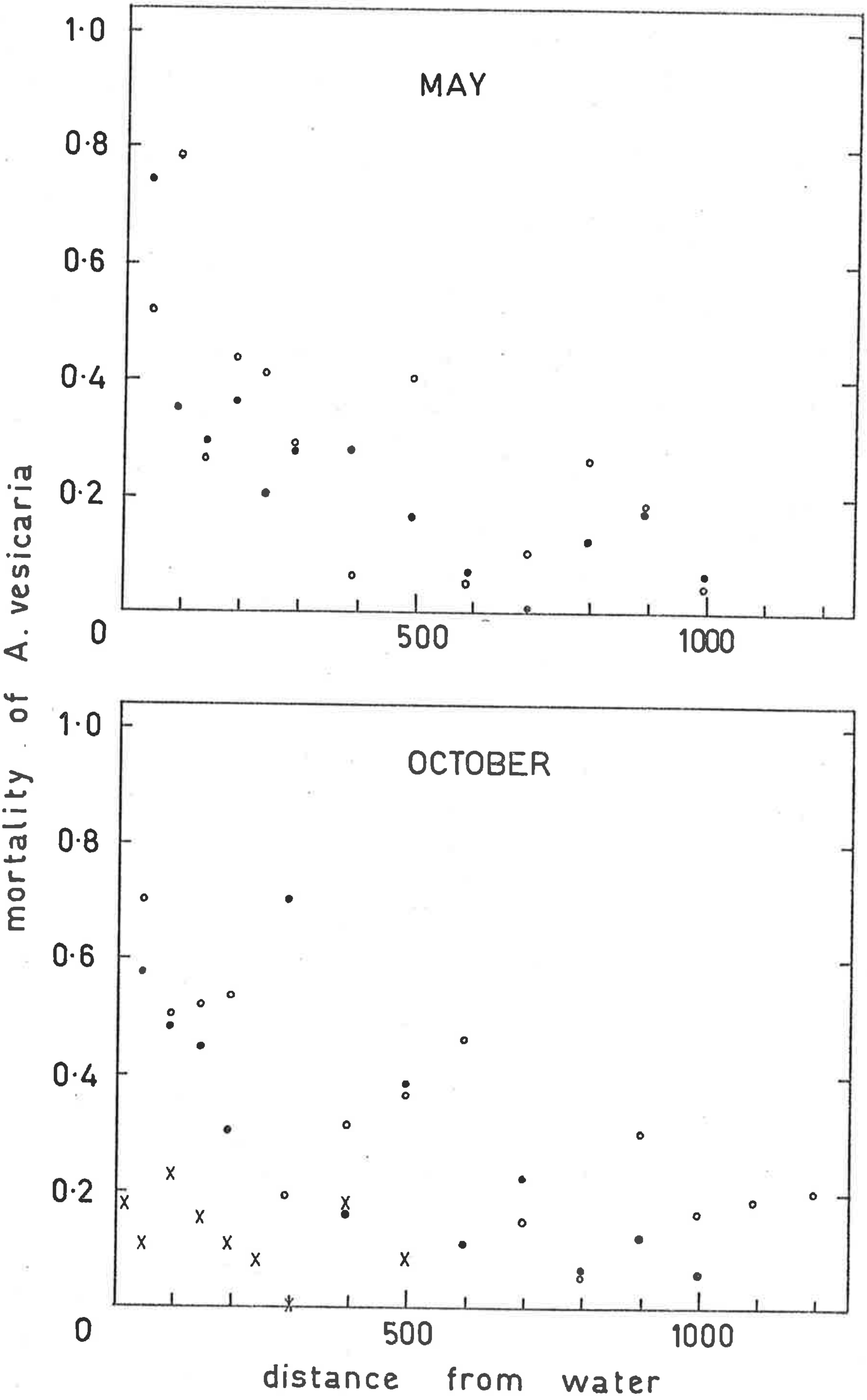


Fig. 11.5b. Mortality of *A. vesicaria* (i.e. % of standing bushes without any live leaves) on same transects as described above.

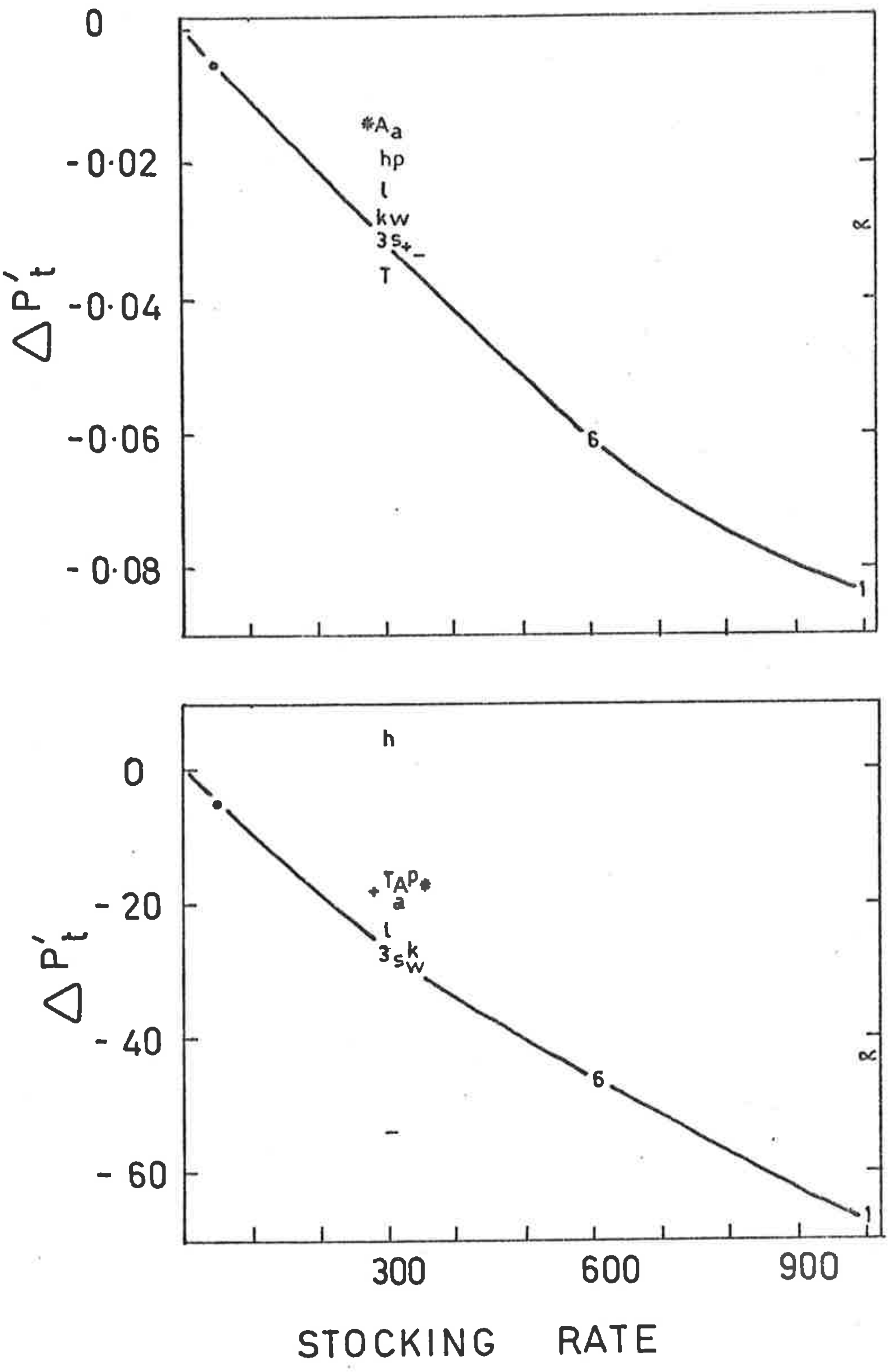


Fig. 11.6a. The relationships between the indices of paddock and sheep condition and the stocking rate in simulation runs with the sheep on the dam. The symbols are the same as those given in table 11.1.

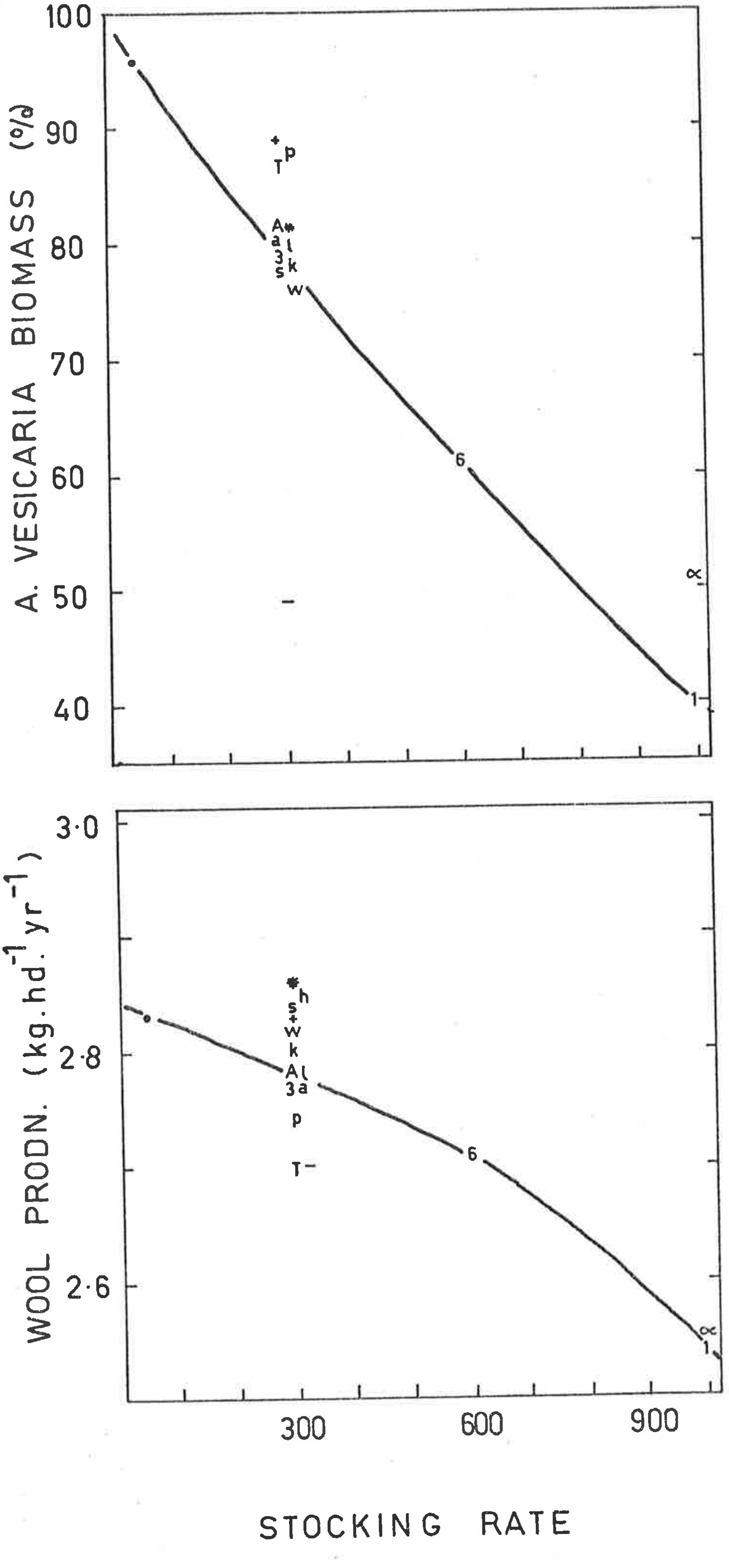


Fig. 11.6b. See 11.6a.

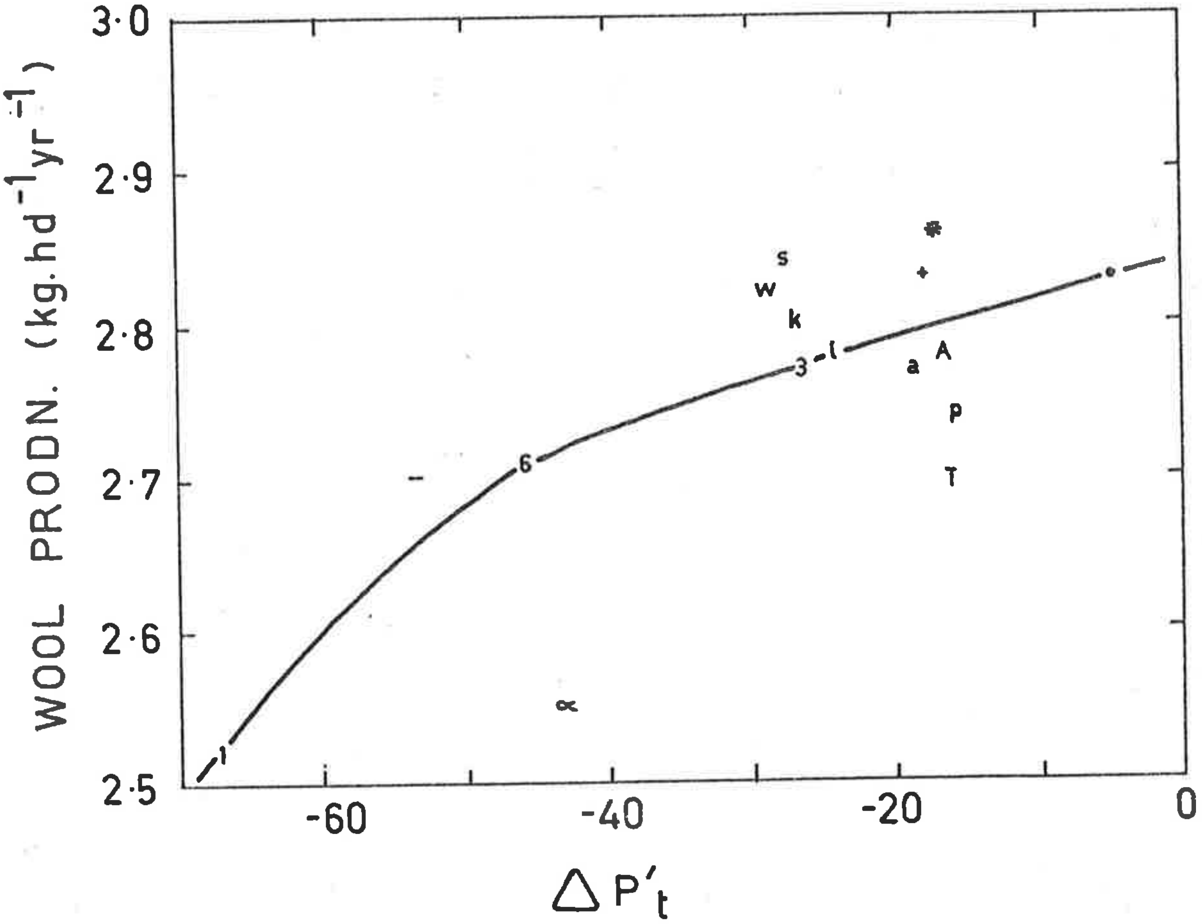


Fig. 11.6c. This figure and figure 11.6d, compare the relationships between various indices of sheep and paddock condition. The solid line in each case joins the series of runs with stocking rates varying from 0 to 1000 sheep.

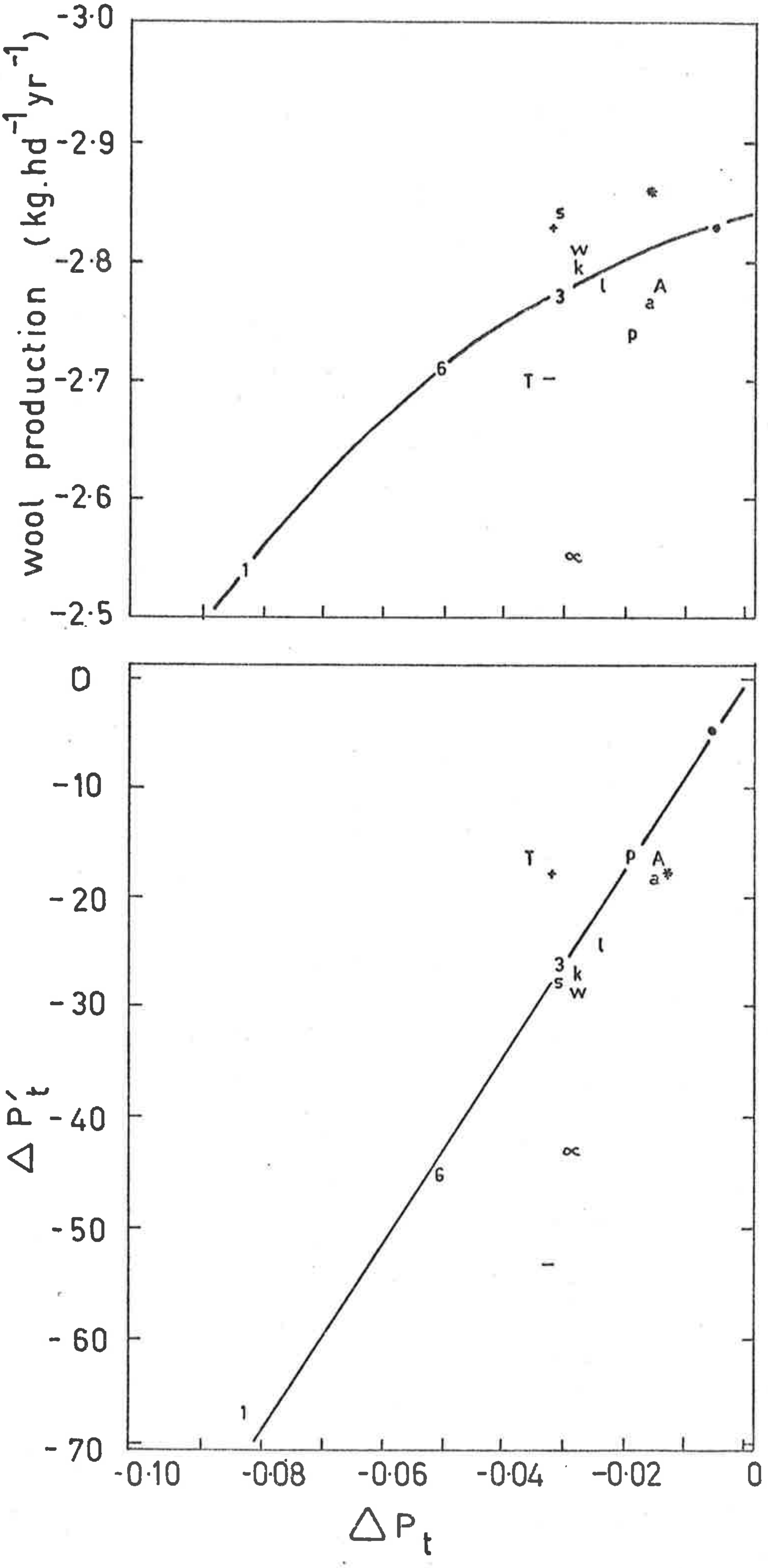


Fig. 11.6d. See figure 11.6c.

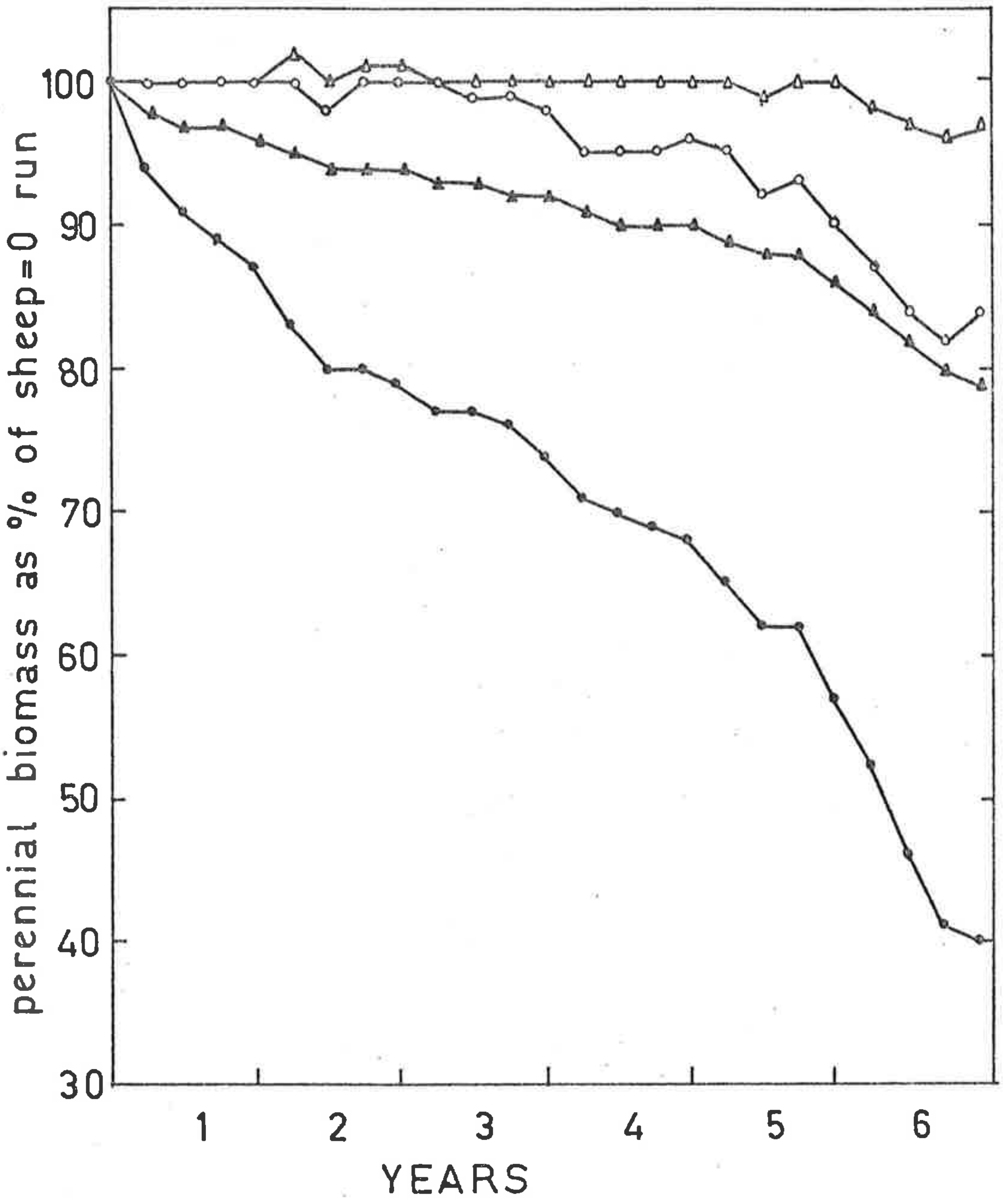


Fig. 11.7. A comparison of the decline in perennial biomass at two stocking rates. The open symbols represent the standard run with 300 sheep in the paddock (R-1) while the solid symbols represent the run with 1000 sheep (R-6) on the dam. *A. vesicaria* biomass is shown by ——O—— and *K. sedifolia* by ——Δ——.

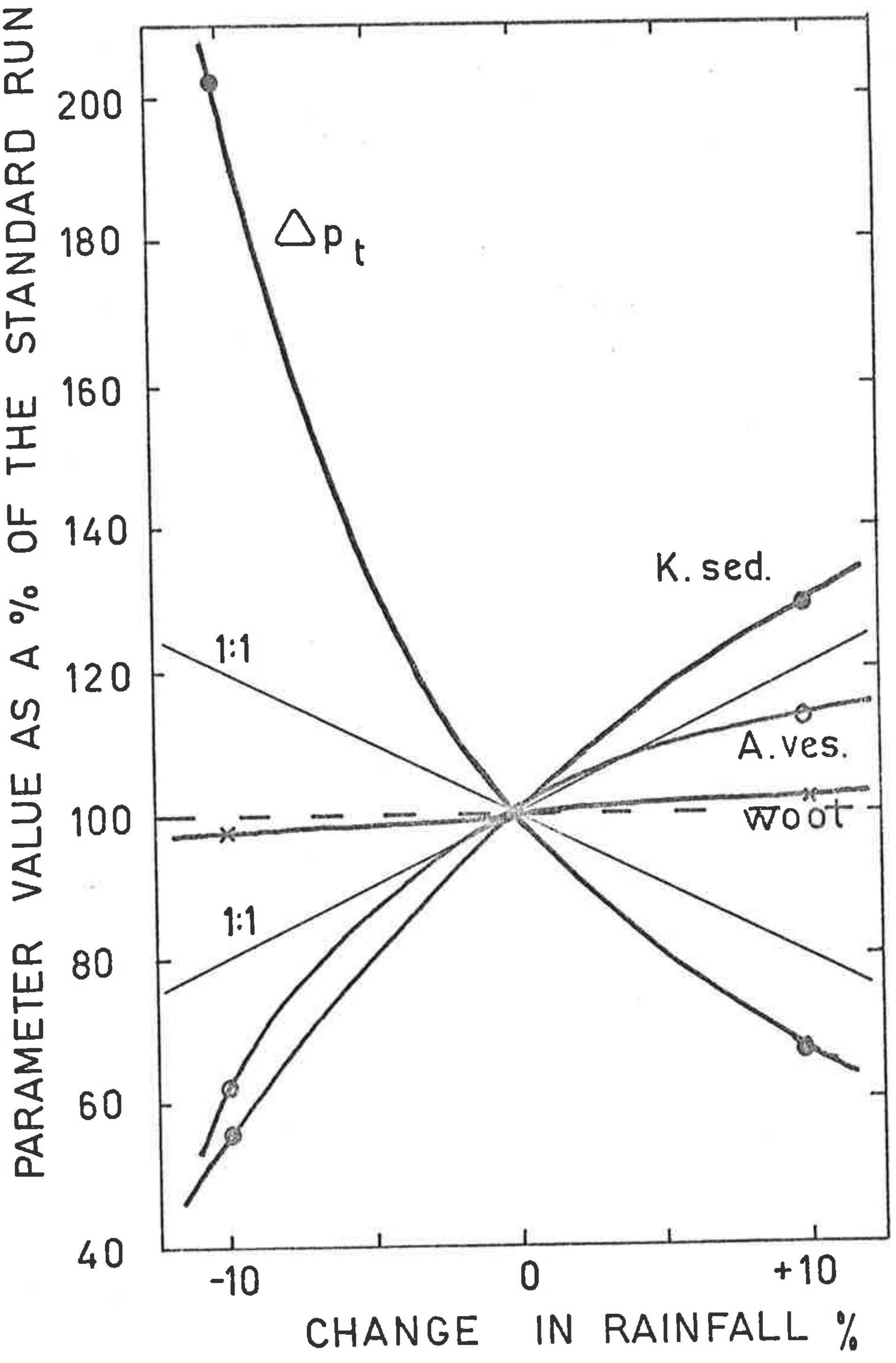
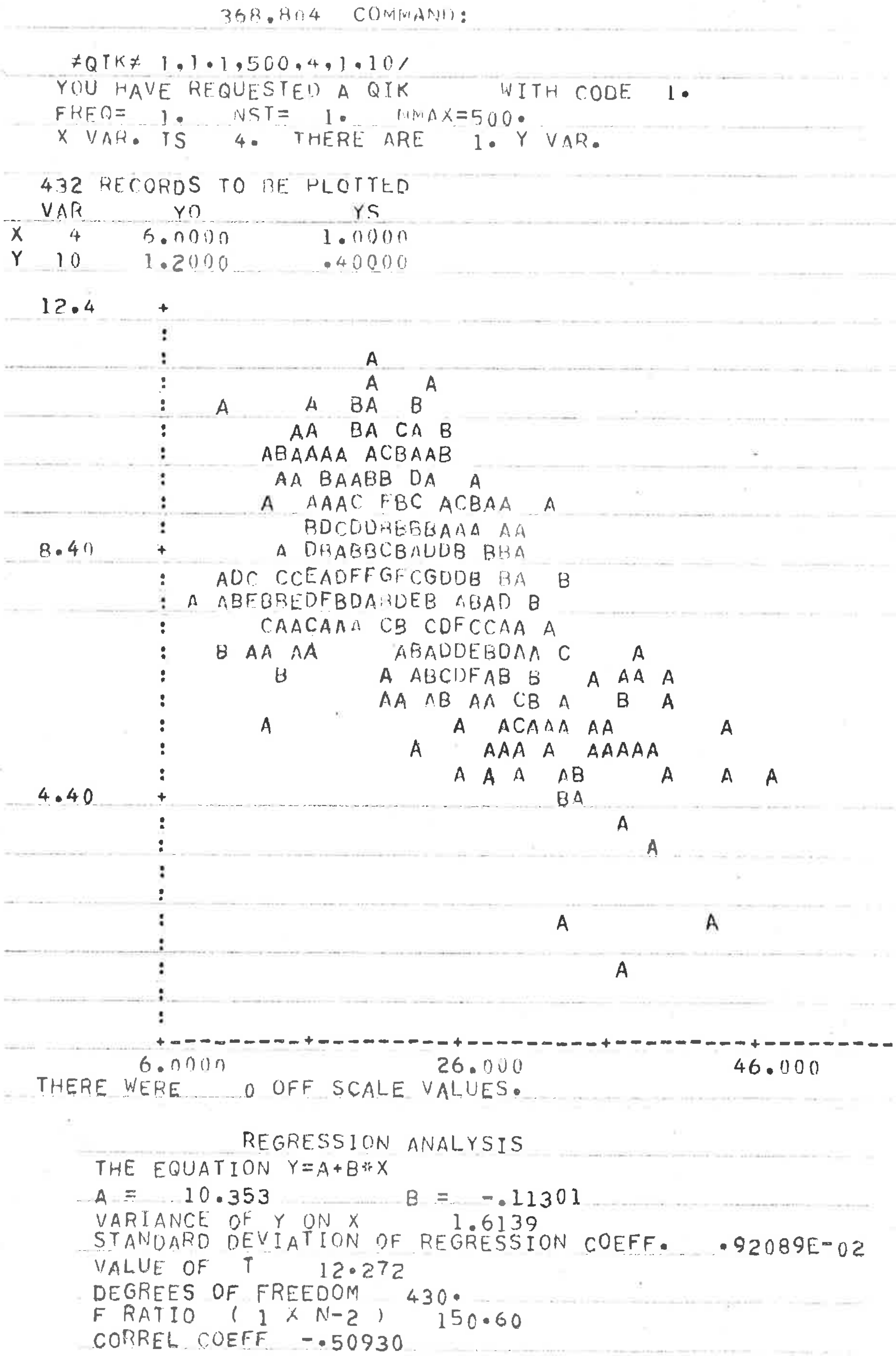


Fig. 11.8. The sensitivity of the model to rainfall. The amount of rain in each event of the standard run was increased or decreased by 10%.



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    YOU HAVE REQUESTED A QIK       WITH CODE  1.
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    X VAR. IS    4.   THERE ARE    1. Y VAR.

   432 RECORDS TO BE PLOTTED
   VAR        YO            YS
X    4      6.0000        1.0000
Y   10      1.2000        .40000

   12.4     +
            :
            :             A
            :             A   A
            :   A     A  BA  B
            :        AA  BA CA B
            :      ABAAAA ACBAAB
            :       AA BAABB DA  A
            :      A  AAAC FBC ACBAA  A
            :         BDCDDBBBBAAA AA
   8.40     +       A DBABBCBADDB BBA
            :   ADC CCEADFFGFCGDDB BA  B
            : A ABEBBEDFBDABDEB ABAD B
            :      CAACAAA CB CDFCCAA A
            :   B AA  AA    ABADDEBDAA C    A
            :       B      A ABCDFAB B   A AA A
            :              AA AB AA CB A   B  A
            :      A            A  ACAAA AA       A
            :                A    AAA A  AAAAA
            :                   A A A  AB     A   A  A
   4.40     +                          BA
            :                              A
            :                                A
            :
            :
            :                          A         A
            :
            :                              A
            :
            :
            +---------+---------+---------+---------+---------
          6.0000              26.000              46.000
   THERE WERE    0 OFF SCALE VALUES.

                REGRESSION ANALYSIS
      THE EQUATION Y=A+B*X
      A =  10.353            B =  -.11301
      VARIANCE OF Y ON X        1.6139
      STANDARD DEVIATION OF REGRESSION COEFF.   .92089E-02
      VALUE OF  T     12.272
      DEGREES OF FREEDOM    430.
      F RATIO   ( 1 X N-2 )   150.60
      CORREL COEFF  -.50930
```

Fig. 11.9. An example of some output from DATAR. This program package analysed data stored on a mass storage device by GRZMOD2. The example above is a plot of grazing time (hr hd^{-1} day) against maximum air temperature (°C).

Run Number	symbol	brief description	
R-1	0	0 sheep	A run with the standard weather sequence and the paddock grazed for 6 years.
R-2	3	300 dam	The 'standard run' with the standard weather sequence and with 300 sheep watering at the dam for 6 years. This presented the normal management practice.
R-3	T	300 trough	As above but with the sheep watering at the trough.
R-4	•	50 dam	As R-2 but with only 50 sheep.
R-5	6	600 dam	As R-2 but with 600 sheep.
R-6	1	1000 dam	As R-2 but with 1000 sheep.
R-7	A	300 D-T	As R-2 but with the sheep alternated between the dam and trough water-point each year. In the first year the sheep were on the dam.
R-8	a	300 T-D	As R-7 except the sheep were on the trough in the first year.
R-9	∝	1000 D-T	As R-7 but with 1000 sheep.
R-10	s	300 D Sept	As R-2 but sheep shorn in September rather than March.
R-11	+	300 D + 10% RF	As R-2 except each rainfall event of the standard weather sequence was increased by 10%.
R-12	-	300 D - 10% RF	As R-11 except that the rainfall events were decreased by 10%.
R-13	l	300 D low RF	As R-2 except a different rainfall sequence was used. This sequence was chosen to be about 10-20% lower than the standard.

Table 11.1 A description of the experimental runs of the model.

R-14	h	300 D high RF	As R-13 except the rainfall sequence was about 10-20% higher than the standard.
R-15	p	300 D pref.	As R-2 except that the sheep's preference for ephemerals was increased.
R-16	k	300 D drink	As R-2 except that the sheep required about 20% less water.
R-17	w	300 D walk	As R-2 except the sheep had a tendancy to walk greater distances, and to move faster.
R-18	*	300 D-T Sept	As R-7 except that the sheep were shorn in September instead of March.

Table 11.1. Continued.

			Δp_t	$\Delta p_t'$	*A. ves.* biomass	*K. sed.* biomass	Peren. biomass	wool prod. %	wool kg hd^{-1}	wool growth rate	mortality %
R-1	0	0 sheep	0	0	100	100	100				
R-2	3	300 dam	-31	-27	79	97	89	100	2.77	2.97	6.7
R-3	T	300 trough	-36	-16	87	92	90	98	2.70	2.88	6.2
R-4	•	50 dam	-5	-5	96	100	98	102	2.83	3.01	6.0
R-5	6	600 dam	-51	-46	61	90	77	98	2.71	2.88	5.9
R-6	1	1000 dam	-83	-67	40	85	63	92	2.54	2.76	8.7
R-7	A	300 D-T	-14	-17	82	95	89	100	2.78	2.96	6.1
R-8	a	300 T-D	-15	-19	81	98	90	100	2.77	2.95	6.1
R-9	α	1000 D-T	-29	-43	51	75	64	92	2.55	2.77	8.7
R-10	s	300 D Sept	-31	-28	78	96	87	103	2.84	3.01	6.1
R-11	+	300 D + 10% RF	-32	-18	89	125	108	102	2.83	2.99	5.3
R-12	-	300 D - 10% RF	-33	-54	49	54	51	98	2.70	2.90	6.7
R-13	l	300 D low RF	-24	-24	80	100	91	100	2.78	2.94	5.5
R-14	h	300 D high RF	-19	+5	110	133	122	103	2.85	3.03	5.8
R-15	p	300 D pref.	-19	-16	88	99	94	99	2.74	2.89	5.3
R-16	k	300 D drink	-28	-27	78	98	89	101	2.80	2.99	6.4
R-17	w	300 D walk	-28	-29	76	100	89	102	2.82	2.99	5.6
R-18	*	300 D-T Sept	-14	-17	83	99	91	103	2.86	2.98	5.4

Table 11.2. A summary of the results of the experimental runs of the model. The parameters are described over the page.

.../2

Description of the parameters

Δp_t	- Change in the piosphere index, p_t, compared with a standard run. The figures in the table have been multiplied by a factor of 1000.
$\Delta p'_t$	- Change in the piosphere index, p'_t, compared with a standard run. The figures in the table have been multiplied by a factor of 1000.
A. vesicaria biomass	- The *A. vesicaria* biomass at the end of the run expressed as a percentage of the *A. vesicaria* biomass at the end of run R-1 (i.e. the ungrazed paddock).
K. sedifolia biomass	- As above, but for *K. sedifolia*.
Perennial biomass	- As above, but for *A. vesicaria* plus *K. sedifolia*.
wool production %	- The total wool clip per head of sheep placed in the paddock, expressed as a percentage of the wool clip in the standard run (R-2).
wool kg hd^{-1}	- The annual average wool clip per head of sheep placed in the paddock.
wool growth rate	- The annual average wool clip per sheep shorn (kg hd^{-1}).
mortality	- The percentage mortality.

Table 11.2. Continued.

	consumption of kg hd^{-1} day^{-1}													
	ephemerals		*A. vesicaria*		*K. sedifolia*		total		grazing time hr day^{-1}		walking distance km day^{-1}		drinking frequency 1 day^{-1}	
	S	M	S	M	S	M	S	M	S	M	S	M	S	M
A	0.39	0.43	0.22	0.27	0.09	0.09	0.90	1.01	7.51	7.93	7.51	8.03	1.22	0.98
W	0.49	0.50	0.23	0.24	0.11	0.10	0.97	0.99	7.79	7.91	7.71	7.75	1.05	0.98
S_p	0.72	0.63	0.23	0.20	0.04	0.09	1.12	0.99	8.97	7.86	8.83	8.32	0.84	1.10
S	0.63	0.59	0.19	0.17	0.08	0.07	1.01	0.94	7.74	7.15	8.43	7.89	1.11	1.11
T	0.56	0.54	0.22	0.22	0.08	0.09	1.00	0.98	8.00	7.71	8.12	8.00	1.06	1.04

Table 11.3. A comparison of various seasonal mean parameter values for the March shearing standard run, M (R-2), and the September shearing, S (R-10).

	consumption of								grazing		walking		drinking	
	ephemerals		*A. vesicaria*		*K. sedifolia*		total		time		distance		frequency	
	kg hd^{-1} day^{-1}								hr day^{-1}		km day^{-1}		1 day^{-1}	
	W	S	W	S	W	S	W	S	W	S	W	S	W	S
A	0.44	0.43	0.30	0.27	0.06	0.09	1.01	1.01	7.83	7.93	9.10	8.03	0.97	0.98
W	0.58	0.50	0.28	0.24	0.06	0.10	0.99	0.99	7.72	7.91	8.69	7.75	0.97	0.98
S_p	0.63	0.63	0.23	0.20	0.05	0.09	0.98	0.99	7.58	7.86	9.15	8.32	1.09	1.10
S	0.59	0.59	0.20	0.17	0.04	0.07	0.93	0.94	6.92	7.15	8.77	7.89	1.16	1.11
	0.56	0.54	0.25	0.22	0.05	0.09	0.98	0.98	7.51	7.71	8.93	8.00	1.05	1.04

Table 11.4. A comparison of various seasonal mean parameter values for the 'walker' sheep, W (R-17), and the standard run, S (R-2).

	consumption of								grazing time		walking distance		drinking frequency	
	ephemerals		*A. vesicaria*		*K. sedifolia*		total							
	kg hd^{-1} day^{-1}								hr day^{-1}		km day^{-1}		1 day^{-1}	
	D	S	D	S	D	S	D	S	D	S	D	S	D	S
A	0.45	0.43	0.28	0.27	0.08	0.09	1.02	1.01	7.88	7.93	7.84	8.03	0.76	0.98
W	0.51	0.50	0.25	0.24	0.09	0.10	0.99	0.99	7.80	7.41	7.50	7.75	0.78	0.98
S_p	0.63	0.63	0.21	0.20	0.08	0.09	0.99	0.99	7.68	7.86	8.02	8.32	0.85	1.10
S	0.59	0.59	0.18	0.17	0.06	0.07	0.94	0.94	6.98	7.15	7.60	7.89	0.91	1.11
	0.55	0.54	0.23	0.22	0.08	0.09	0.99	0.98	7.59	7.71	7.74	8.00	0.83	1.04

Table 11.5. A comparison of various seasonal mean parameter values for the sheep with a reduced water dependency, D (R-16), and the standard run, S (R-2).

	consumption of kg hd^{-1} day^{-1}													
	ephemerals		*A. vesicaria*		*K. sedifolia*		total		grazing time hr day^{-1}		walking distance km day^{-1}		drinking frequency 1 day^{-1}	
	P	S	P	S	P	S	P	S	P	S	P	S	P	S
A	0.54	0.43	0.14	0.27	0.05	0.09	1.02	1.01	7.88	7.93	7.73	8.03	0.76	0.98
W	0.59	0.50	0.15	0.24	0.06	0.10	1.00	0.99	7.84	7.91	7.42	7.75	0.82	0.98
S_p	0.74	0.63	0.14	0.20	0.05	0.09	1.03	0.99	8.08	7.86	8.21	8.32	0.95	1.10
S	0.70	0.59	0.10	0.17	0.02	0.07	0.98	0.94	7.31	7.15	7.84	7.89	1.00	1.11
	0.64	0.54	0.13	0.22	0.05	0.09	1.01	0.98	7.78	7.71	7.80	8.00	0.88	1.04

Table 11.6. A comparison of various seasonal mean parameter values for the sheep with a greater preference for ephemerals, P (R-15), and the standard run, S (R-2).

		regression analysis		
Y variable	X variable	a	b	σ_b
drink (ml hd^{-1} day^{-1})	air temperature (°C)	2032	40.1	6.3
walking (km hd^{-1} day^{-1})	air temperature (°C)	8.93	-0.041	0.010
grazing time (hr day^{-1})	air temperature (°C)	10.4	-0.113	0.0092
A. ves. consump. (kg hd^{-1} day^{-1})	air temperature (°C)	0.320	-0.00431	0.00095
total consumption (kg hd^{-1} day^{-1})	air temperature (°C)	1.28	-0.0121	0.00083
drink (ml hd^{-1} day^{-1})	A. ves. consump. (kg hd^{-1} day^{-1})	1951	4507	246
drink (ml hd^{-1} day^{-1})	K. sed. consump. (kg hd^{-1} day^{-1})	2270	7625	276
drink (ml hd^{-1} day^{-1})	grass (kg hd^{-1} day^{-1})	4179	-2621	94.5
drink (ml hd^{-1} day^{-1})	total consumption (kg hd^{-1} day^{-1})	5486	-2548	289
walking (km hd^{-1} day^{-1})	total consumption (kg hd^{-1} day^{-1})	3.07	4.92	0.44
walking (km hd^{-1} day^{-1})	grazing time (hr day^{-1})	1.34	0.856	0.024

Table 11.7. An example of some of the linear relationships determined from the model output. These data were determined by using DATAR on a file saved from run R-2.

DISCUSSION

12.0 *Introduction*

In this final chapter I discuss two points. First, how successful was the project in achieving the aims stated in section 3.5, and second, what implications does the project have for arid zone grazing management and research?

12.1 *The aims of the project*

Four aims for the project were listed in section. 3.5. These are restated, and discussed below.

12.11 *To gather data (from the literature, by reassessing old records, and from original experimentation and observation) describing the important interactions in the Australian arid zone sheep paddock system.*

The data gathering was the most time consuming part of the project. The literature review produced over 1200 references which were maintained on a computer based library. About 350 of the references are included in this thesis. The review was not 'comprehensive' and 'exhaustive' (section 3.2) but it did reveal the areas of strength and weakness in the arid zone literature base. There is a distinct shortage of field based and long term experimental studies of plant growth dynamics and sheep behavioural work. This was not unexpected. More important, is the criticism that many of the field studies have been piecemeal and ad hoc, making quantitative, and even qualitative, comparison between separate studies very difficult. This is probably a result of the nature of the research projects in Australia. Until recently, most arid zone work has been conducted by University based staff and especially research students, who are of necessity based long distances from their study sites and are limited in the duration of the project, their technical assistance and their ability to conduct widely co-operative work. The role of government agencies has tended to be oriented more towards the solution of particular problems and administrative and extension duties. The arid zone based research groups (mainly, C.S.I.R.O. and some government groups) now offer an opportunity for more integrated and longer term studies.

Other fields have a better literature base. Arid zone climatology, meteorology and hydrology is relatively well researched and reported, although there is always a need for more weather recording stations in arid areas.

The project placed little emphasis on the sheep physiology and nutrition part of the system. A large amount of experimental data exists, but this is largely laboratory based, and it is doubtful whether it is directly applicable to the field situation.

The original experimentation and observations included in this project has made some contribution to the pool of arid zone data.. The sheep observation work is mainly confirmatory of observations made elsewhere and indicates the need for a suitable automatic monitoring system for gathering sheep behaviour data. The grazing trials were the first quantitative attempt to determine sheep selective behaviour in the South Australian arid zone.

The most important set of original data is the analysis of the Koonamore Vegetation Reserve photographic record. This is the longest sequence of biomass dynamics data that I know to exist for any arid zone site in Australia, and possibly elsewhere. Although the method by which the data were assessed is indirect, I believe it to be accurate, and indicative of the wealth of information available in such a set of records.

12.12 *To determine the most promising approach to at least some of the submodels of components of the system.*

This aim was discussed in each of the chapters describing the submodels, but the important conclusions will be summarized here.

There are many different models describing single components of the weather of a particular site. It appears that models based on Markov processes are the most promising. However, there has been insufficient attention paid to describing models of the complete weather pattern, and it is probably more important to tackle this problem, rather than to improve the models of individual components.

The growth model presented in this thesis was very much ad hoc and limited by the data available. However, the weakness of the essentially exponential growth models which have been used in grazing simulations was emphasised. It is likely that growth models incorporating much more detail about the uptake and competition for the limiting nutrients and soil moisture will be needed if simulation is to be a directly useful tool to managers.

I think the most important submodel developed in this project was that of sheep movement and behaviour. This submodel appears to be unique in grazing models. It does demonstrate that the major aspects of animal behaviour can be accounted for by models based on basic principles of physics and animal physiology. The present submodel is still inadequate in many ways. For example, Wertigo was chosen as the study paddock, partly because it was relatively homogenous and did not include obvious 'prefered' grazing sites. However, this model demonstrates that the approach is sound, and offers a starting point to either the inclusion of more detail (e.g. learning processes) or more simplification (e.g. the use of empirical water and heat balance equations).

12.13 *To construct a model to describe a particular arid zone paddock and to validate this to the maximum extent possible.*

The model finally constructed, appears to be more detailed than any paddock model yet published. It is very specific to Wertigo and sacrifices generality to realism and precision. However it would be simple to modify it to simulate a different paddock in the same area. The main task would be determining the sheep camp sites and shade areas and re-coding the sheep movement model to describe the new paddock shape. Application of the model to a paddock in an area with different soil, vegetation or climate would require more extensive modifications, mainly in the form of new submodels such as soil moisture and plant growth. However they could easily be inserted into the present model by replacing the appropriate subroutines.

The validation of the submodels and complete model has had to be subjective, relying very much on a form of 'Turing's test'. Nevertheless it appears to be realistic as far as can be determined. Several potentially important interactions have been omitted and the results must always be interpreted with this in mind.

12.14 *In constructing the model, to bear in mind its applicability to answering some of the major questions facing both station managers, and arid zone researchers.*

The model is of limited direct value to managers because of the uncertainty about some of the interactions, and because it has only been applied to one paddock and over a relatively short time period. However, the experimental runs in chapter 11 have indicated that many of the management options available to the station managers may be relatively ineffective when compared to the natural variability of the system. Similarly, the experimental runs with the 'new breeds' of sheep indicate that major changes in the adaption of merino sheep to the area may produce only very small changes in paddock condition and productivity.

There are still many other types of experiments which could be performed on the model. More detailed monitoring of the development of the piosphere through time is one example, and runs with a greater variety of weather patterns is another.

12.2 *Further work*

Much of the experimental and field work that could be done in order to improve the final model has been mentioned elsewhere. For example, improved estimates of evapotranspiration rates, soil field capacities, and the sheep nutrition equations, etc. will improve the precision of the final model, while a restructuring of the plant growth model and the estimation of new variables better describing the competition for limited resources will improve the realism of the model. However, improvements to the final model will only be of value if the model is to be developed further for use in other experimental programmes. For example, an intensive study of the development of a piosphere around a previously ungrazed water-point has been started in the Botany Department, and the model would be a useful aid in this programme.

The development of some of the submodels for application in different situations would be a potentially more useful extension of the project. Modelling has often been described as a balance between three goals; realism, precision and generality. I would include efficiency as a fourth goal. Efficiency is a balance between the cost of the model and the success with which it fulfils its purpose. The cost is not only the monetary or time cost in constructing the model, but also includes the cost of maintaining un-needed realism, precision or generality in a model.

In this project I have tended to emphasise realism and precision at the expense of generality. Efficiency has not been a major goal, but it has been taken into account in each submodel. Further effort could be expended in increasing the generality of some of the submodels. Even if the model is developed no further, the work described in this project should be a useful aid in the building of other grazing models.

APPENDIX 1

Energy flow in Wertigo paddock

The following calculations are based on Wertigo paddock. It is assumed to be 2200 ha in area and to carry 250 ewes all year, and 125 lambs for half of the year. A kangaroo population equivalent to 40 adults is assumed. The wooded areas (which cover < 10% of Wertigo) are not considered.

(1) The solar radiation load is about $1.6 * 10^6$ Kcal m^{-2} yr^{-1} (Specht, 1972).

(2) The net primary production of the ephemerals varies from year to year, but the K.V.R. records indicate that a peak biomass of about 100 to 150 g m^{-2} is produced about one year in three. This, along with a few smaller inputs, gives a mean NPP of about 50 g m^{-2} yr^{-1}.

(3) The net primary production of the perennials bears no direct relationship to their standing biomass. However if it is assumed that there is no long term change in standing biomass, then NPP must be balanced by turnover losses and direct heterotroph consumption losses. Charley & Cowling (1968) showed that the leaf turnover for *A. vesicaria* was about 80%, while the biomass of fruit produced was about 40% of the leaf biomass. Therefore, allowing for fruiting to occur less than once per year, the turnover of leaf and fruit production is probably about equal to the mean standing leaf biomass, i.e. about 50 g m^{-2} yr^{-1} for Wertigo. The stem (wood) turnover was about 4%, which implies a production of

about 5 g m^{-2} yr^{-1} in Wertigo (see table 6.1). The total above ground perennial turnover therefore is about 105 g m^{-2} yr^{-1}.

The main vertebrate consumers are ewes, lambs and kangaroos. If the respective consumptions are 1.2, 0.6 and 1.0 kg $head^{-1}$ day^{-1}, the total annual consumption loss is approximately 6 g m^{-2} yr^{-1}. Observations in Wertigo indicated that there was little direct invertebrate consumption of living ephemeral or perennial material. The main exception is the grasshopper plagues which are discussed below.

Therefore the annual, above ground NPP is approximately 110 g m^{-2} yr^{-1}. The root productivity is difficult to estimate but it is assumed that the NPP:mean biomass is the same above and below ground and therefore the root productivity is about $^1/_3$ of the ground productivity (based on the estimates of Charley & Cowling, 1968), giving a total NPP of 150 g m^{-2} yr^{-1}. The energy content of plant material is approximately 4.5 kcal g^{-1} (Odum, 1971) and therefore the NPP may be expressed in round figures as 600 kcal m^{-2} yr^{-1} or 800 W ha^{-1}. This is in about the middle of the range of NPP for desert scrub as estimated by Whittaker (1970).

(4) The gross primary productivity may be estimated if the autotroph respiratory losses are known. Lindeman (1942) argued that primary producers respire about $^1/3$ of the energy they gain through photosynthesis, which gives an estimate of GPP of about 900 kcal m^{-2} yr^{-1} or

1200 W ha^{-1}.

(5) The gross energy intake by herbivores was calculated in (3) as 6 g m^{-2} yr^{-1} or 27 kcal m^{-2} yr^{-1}. The assimilation is much less than this since much of the energy is lost in faeces and urine. If the metabolic energy required for maintenance (MERM) is assumed to be twice the basal metabolic rate, then the MERM for ewes, lambs and kangaroos respectively, are 2400, 1200 and 2000 kcal day^{-1}. The respiratory losses (MERM) are therefore 12 kcal m^{-2} yr^{-1}.

Assimilated energy is stored in the herbivore population. Wertigo produces 125 lambs each weighing about 8 kg (dry weight) each year, i.e. 1000 kg yr^{-1} at an energy content of 5.6 kcal g^{-1} (Odum, 1971), or 0.25 kcal m^{-2} yr^{-1}. About 8 of the 40 kangaroos would die each year, so there must also be sufficient accumulated energy to replace them. This amounts to about 100 kg (dry weight) or about 0.03 kcal m^{-2} yr^{-1}, with an equivalent amount of carcasses being produced. About 10 ewes and a higher number of lambs would die each year contributing about another 0.05 kcal m^{-2} yr^{-1} of carcasses. However, only the lamb proportion of this was actually assimilated in Wertigo, since the ewe numbers are maintained by imports from other paddocks.

The fleece is another major store of assimilated energy. The total clip for Wertigo is about 1000 kg (clean wool), with an energy content of about 6 kcal g^{-1} (section 9.2), i.e. a production of 0.3 kcal m^{-2}

yr^{-1}.

The total assimilation is therefore less than 13 kcal m^{-2} yr^{-1}, or about 47% of the gross energy intake. This is in good agreement with the approach taken in section 9.2 where the digestible energy intake is estimated to be about 60-70% of the gross energy intake and the metabolizable energy intake about 80% of the digestible energy intake.

(6) The total energy flow is shown in figure A.1. The results emphasise the importance of saprobes in the system. The invertebrate consumption of living plant material is difficult to estimate, but is probably very low except in rare events such as grass-hopper plagues. The direct effect of a plague would be to redirect some of the litter pool to the animal dung and dead animal pool.

The effect of the vertebrates seems to be very small. However, the energy flow presented represents mean conditions. In some years the GPP would be reduced many fold, making the vertebrate consumption very significant. Also, the vertebrate consumption tends to be concentrated in certain areas, and at some sites near water the vertebrate consumption is many times higher than the mean, while the GPP is reduced due to reduced biomass. Invertebrates, such as grass-hoppers do not show this tendancy for local (i.e. intra-paddock) concentration during plagues, and therefore tend to be concentrated in time rather than space.

(7) The contribution to NPP due to the trees is difficult

to estimate and is not discussed here. However the total tree biomass in Wertigo is approximately 7000 t including 1000 t of leaf (based on Correll, 1967), compared with 800 t of perennial bush leaf. 90% of the tree biomass is contained in the two blackoak groves which occupy less than 5% of the paddock area and therefore has little effect on the paddock as a whole.

(8) Recently, Caldwell & Camp (1974) have published estimates of the below ground productivity of *Atriplex confertifolia* in a cool desert. This species has a root : shoot ratio of 7:1 and a root productivity 3 times that of the shoots. This indicates that my estimate of root productivity may be much too low. However this would have little effect on the arguments above since increased root productivity would simply increase the size of the flow to root decomposition and would have no effect on the above ground component.

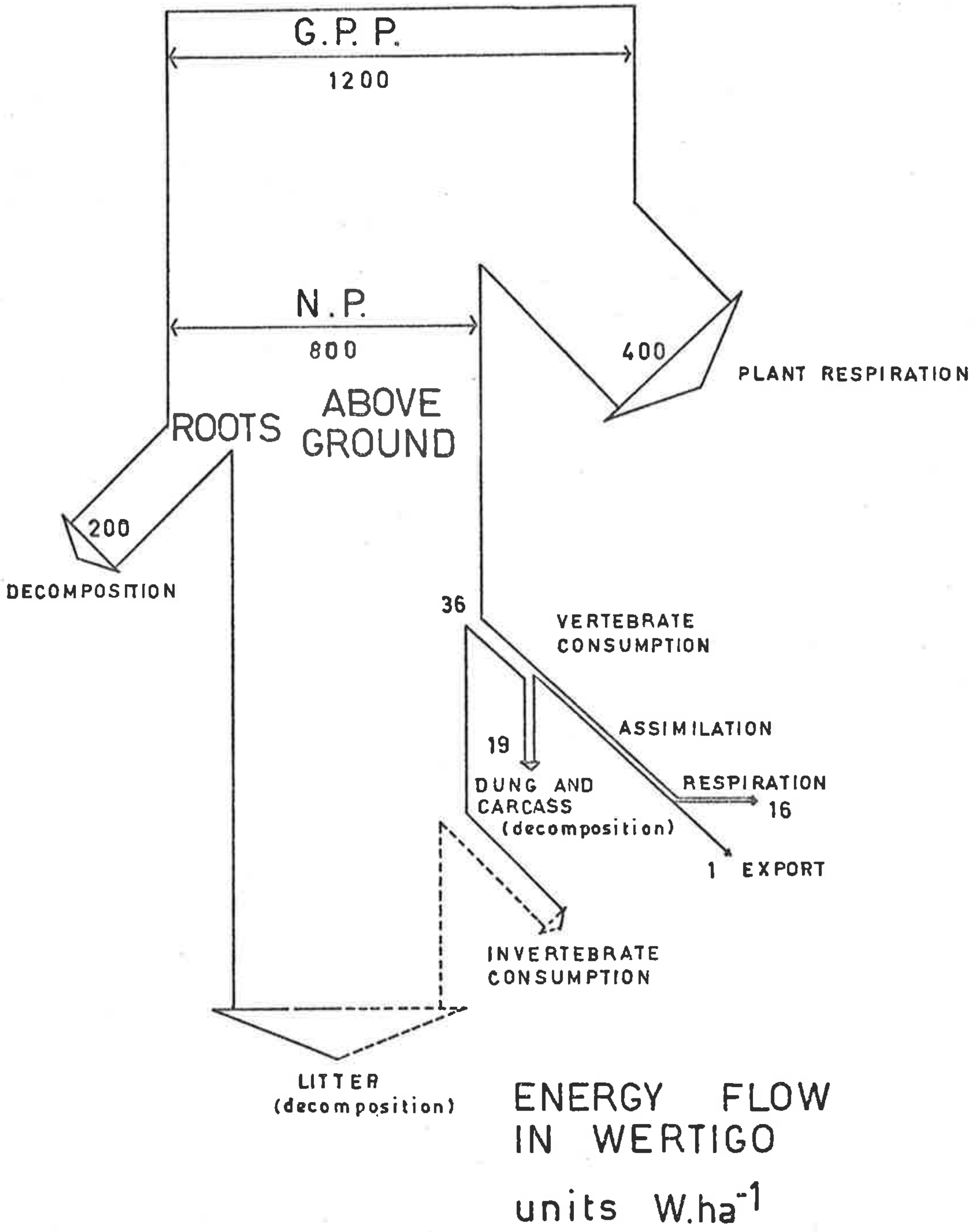

Fig. A.1. Estimated energy flow through Wertigo. The flows are mean annual values (1 W ha^{-1} = 1.33 kcal m^{-2} yr^{-1}).

APPENDIX 2

The Yudnapinna experiment

The Yudnapinna experiment, and more particularly the Trumble & Woodroffe (1954) paper describing it, is problematical. It is often quoted, along with the paper of Osborn et al. (1932), as evidence that moderate to heavy grazing of shrublands can lead to an improvement in bush condition. However there are several unsatisfactory aspects about their reporting of the grazing trials, and I discuss them further in this appendix.

Trumble & Woodroffe describe a "marked improvement of the bluebush on grazed plots relative to the ungrazed", and during the wet seasons of the latter half of the experiment there was "an extraordinary increase in the weight of bluebush on the moderate to very heavily grazed plots". As their main evidence, and main item of visual impact, Trumble & Woodroffe present a diagram of 'adjusted' biomasses for the control plot and four of the trials (presented here as fig. A2.1). Here lie the first problems. Their paper describes only four of the 13 experimental treatments originally set up (Woodroffe, 1941), and the 'intermittent very heavy grazing' trial is not fully described. Not only was the stocking rate in this trial changed in 1947, but also, the method of spelling the paddock is not described. It is therefore misleading to include this trial with the series of increasingly higher fixed stocking rate trials, when discussing the results.

The 'adjustment' used in their results is another problem. Trumble & Woodroffe describe it as follows:

> "It has been found possible by correlation and regression to eliminate the direct effect of season on the weight of the

> bluebush forage in the grazed plots, and to convert these weights to a 'constant season' basis, represented by the mean of the control plot".

I have attempted to discover what the actual adjustment was, and have found that it can be approximated by,

$$C_i = 987 + 0.930 * (B_i - N_i) \qquad (r_{46} = 0.957)$$

where C_i is the adjusted weight in year i, B_i is the actual biomass of the grazed trial and N_i is the actual biomass of the ungrazed trial (all weights are lb acre^{-1} of green biomass) (fig. A2.2). The mean weight of the ungrazed trial was 974 lb acre^{-1}, and therefore the adjustment probably included the term,

$$C_i = \bar{N} + (B_i - N_i).$$

The scatter remaining in figure A2.2 may possibly be accounted for by smoothing the B_i and N_i values by correlating them with influential rainfall, but I have not been able to find the actual correction. The adjusted data are essentially the difference in biomass between the grazed and ungrazed trials.

Another important point to be borne in mind is the actual grazing pressure being exerted on the bluebush. *K. Sedifolia* is not much prefered by sheep and is usually only consumed when little other forage is available. The latter part of the experiment experienced exceptionally wet conditions with 6 out of the final 7 years having greater than the mean annual influential rainfall. Both of these points are recognized by Trumble & Woodroffe and therefore it is surprising that they do not present more data for other species. Even in the heavy trial, the 18 sheep in the enclosure would only consume about 36 000 lb of forage per year, yet at times there were 368 000 lbs of 'other forage' present. These omissions make the results very difficult to interpret.

Figures A2.3, A2.4 and A2.5 show plots of the uncorrected data presented only in tabular form by Trumble & Woodroffe. I believe that it is clear from these plots, that the heavy grazing treatment did not result in any significant improvement over the ungrazed trial. The biomass (fig. A2.3) declined relative to the ungrazed trial from 1940 to 1945, and even during the exceptionally wet years from 1946 to 1952 there was little improvement. The 1946 rains did result in a large number of seedling blue-bushes (fig. A2.4) and presumably some increase in the weight of the mature bushes since the mean bush biomass did not fall (fig. A2.5). However, only about 20% of the seedlings survived, despite the good follow up years. The moderate and, to a lesser degree, the light grazing trials do show some improvement over the ungrazed trial throughout the 12 years of the experiment.

In summary, I do not disagree with Trumble & Woodroffe's conclusion that grazing can lead to an improvement in bush condition and that this improvement is largely, but not entirely, due to the increased establishment of seedlings. I have noted a similar increase in seedling numbers in my grazing trial enclosures during the first year or more after the trial. However, it is misleading to imply that this will occur even under continuous heavy or very heavy stocking. The very heavy stocking was only intermittent with the stocking rate probably being adjusted with the conditions, while the results of the heavy fixed stocking trial are not conclusive. I also question the applicability of the stocking rates to large paddock situations. Many studies have shown that the grazing impact of sheep tends to be concentrated in the area nearest water. This was recognised by Trumble & Woodroffe and the stocking rates used in the trial were deliberately higher than those used in the district (e.g. a moderate stocking rate of 48 sheep per square mile, compared with the 'conservative' average of 22 sheep per square mile on Yudnapinna station [Woodroffe, 1941]). But my experience in Wertigo would indicate that this was insufficient to account for the differences between flocks of 16 sheep (the moderate trial) and 200 to 300 sheep (a Yudnapinna paddock) on a water-point.

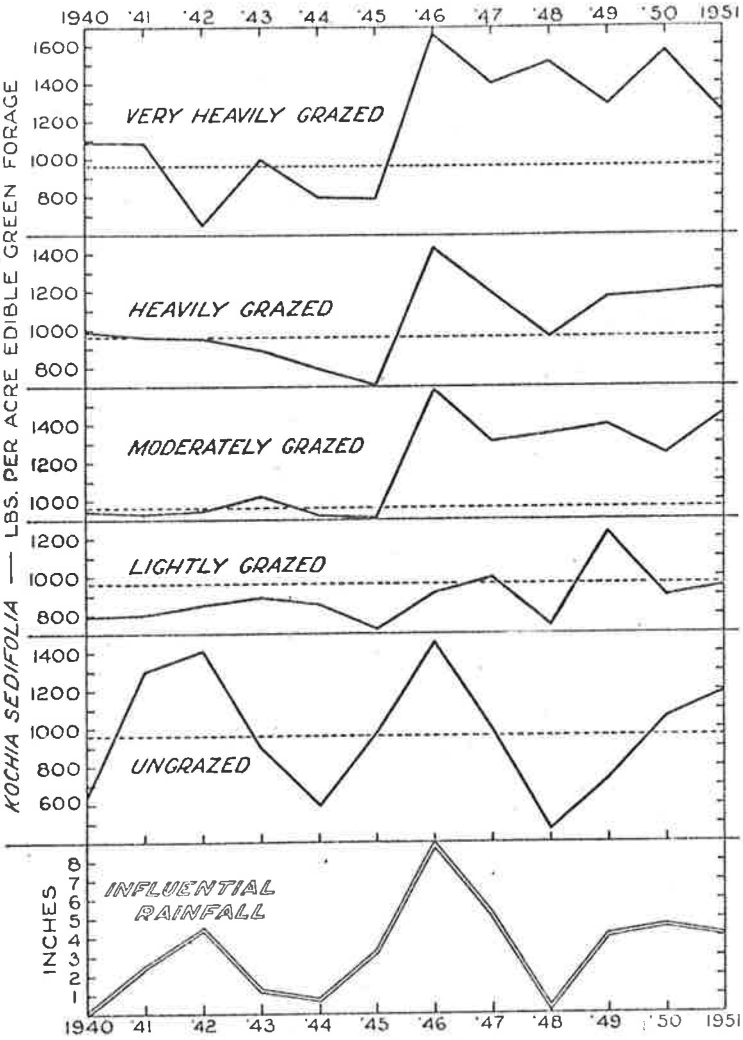

Figure 5.

Weight of *Kochia sedifolia*, estimated in September, on plots grazed at different rates of Stocking — Yudnapinna.

Actual weights of forage are shown for the ungrazed control plot to indicate seasonal fluctuations. For the grazed plots weights of forage have been adjusted relative to the ungrazed plot to eliminate the direct effects of season, and the mean of the ungrazed plot (broken lines) is shown for comparison.

Fig. A2.1. The results of some of the Yudnapinna grazing trials. The biomasses of the grazed trials are presented in an 'adjusted' form. (From Trumble & Woodroffe, 1954).

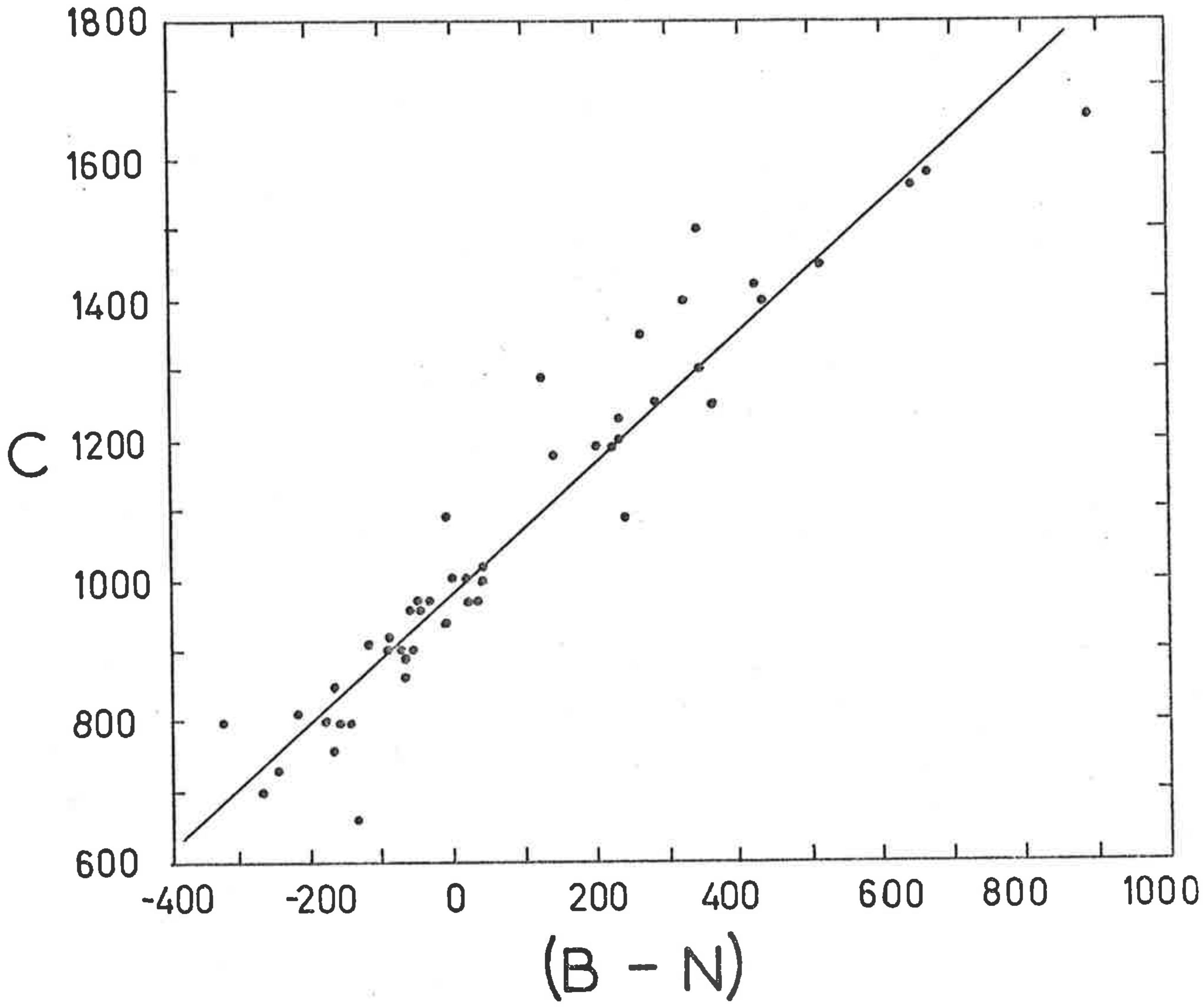

Fig. A2.2. The relationship between C, the 'adjusted biomass' used by Trumble & Woodroffe (1954), and the difference between the actual biomass in a given trial and the actual biomass in the ungrazed trial (B-N). The data from all the trials presented by Trumble & Woodroffe are pooled in this figure. The line is the best fit by least squares analysis.

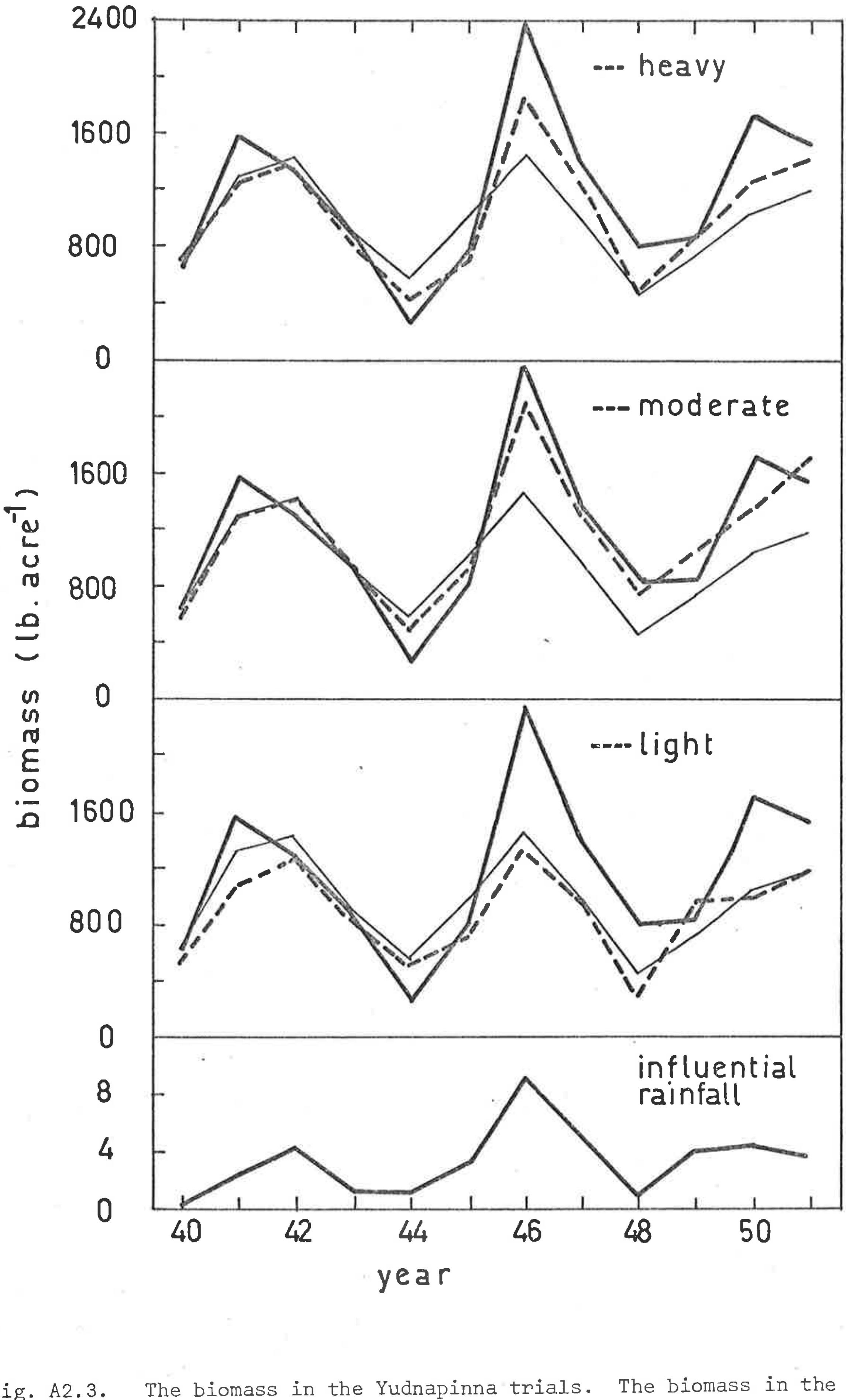

Fig. A2.3. The biomass in the Yudnapinna trials. The biomass in the ungrazed trial (light line) and the very heavy trial are shown in each graph.

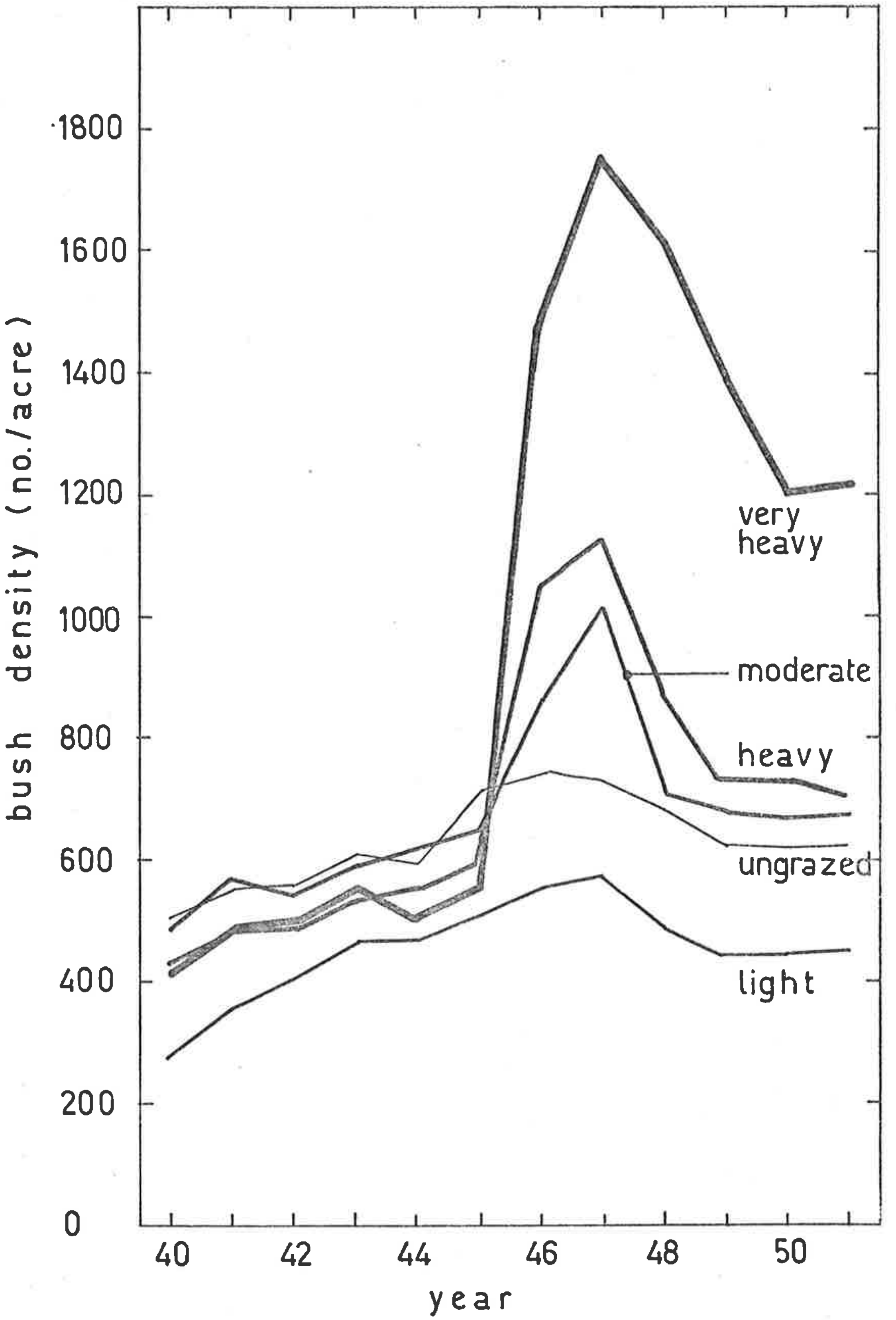

Fig. A2.4. The mean bush density in each of the Yudnapinna trials showing the increased response in density with increasing grazing pressure.

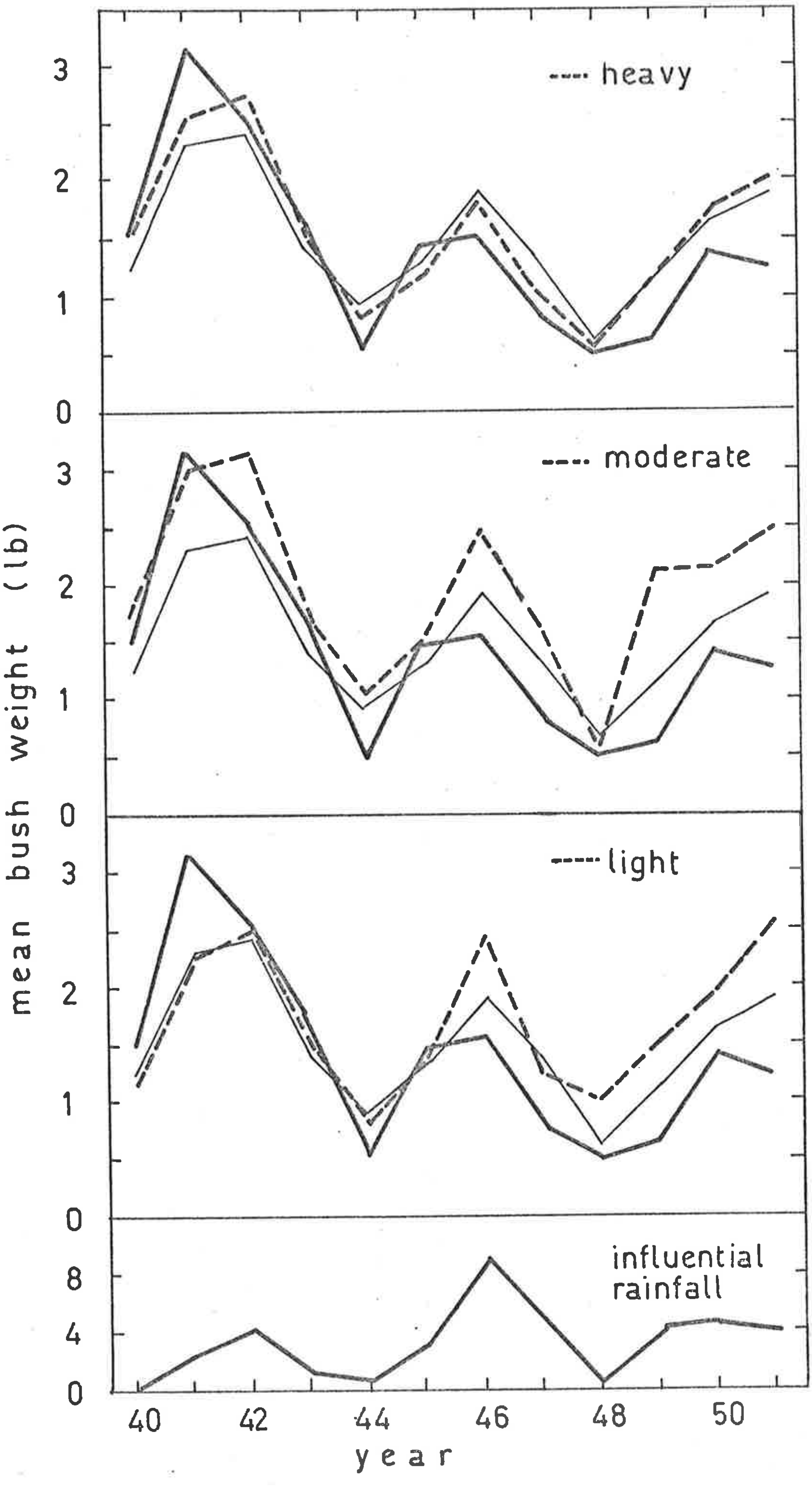

Fig. A2.5. The mean bush weight in the Yudnapinna trials. The mean weight in the ungrazed trial (light line) and the very heavy trial (heavy line) are shown in each graph.

APPENDIX 3

The oesophageal fistula technique

The oesophageal fistula technique of dietry sampling has proved useful in many parts of the world. However there are many disadvantages associated with it. The animals are more difficult and expensive to maintain and suffer a higher mortality than normal sheep. There is also always a possibility that the fistulated animals are behaviourally abnormal. Peden et al. (1974) have recently described a technique where oesophageal fistula results are used along with faecal sampling in an attempt to increase the sampling efficiency and to obtain results from a relatively more normal group of animals.

In this appendix, I discuss the results of Leigh & Mulham (1966a, b; 1967). I use these results only as an example of the problems of interpreting oesophageal fistula data in arid zone shrubland situations, and I do not wish to challenge Leigh & Mulham's general conclusions.

Leigh & Mulham describe three trials in which an enclosure of 0.1 acres (0.04 ha) was subjected to heavy grazing by 4 to 6 sheep so that the biomass declined rapidly over 4 to 6 days. They made daily estimates of both the species biomass, which were accurate to ± 20% for most species, and of the percentage contribution of each species to the diet as estimated from the oesophageal fistula extrusa. In the absence of trampling losses and with accurate biomass estimation, the percentage contribution of each species to the total loss of biomass each day should be equal to the percentage contribution to the diet as estimated from the fistulated animals. However trampling losses are difficult to estimate, and thus little can be determined about the accuracy of the oesophageal fistula technique via this approach.

Nevertheless the average total daily consumption of merino wethers is known at least approximately, and the daily consumption of a species may be estimated by multiplying its percent contribution to the diet as estimated from the fistula sample, by the total daily consumption. The result should be somewhat less than the estimated loss in biomass over that day since trampling losses also have to be allowed for.

I tested whether this was so in Leigh & Mulham's data by using the grasses (both perennial and annual) as an example. The mean daily consumption of a merino wether is about 1.2 kg hd^{-1} day (dry weight), or 2.6 lb hd^{-1} day^{-1}, but this would be reduced as the biomass available in the enclosure fell. The mean biomass loss per head per day was estimated from Leigh & Mulham's biomass estimates, and I assumed that 50% of the loss was due to consumption (compared with 63% in my own trials, section 7.42). This led to the predicted consumptions given in table A3.1. Although the assumptions concerning the total daily consumption were deliberately conservative (i.e. towards under-estimation), 9 out of the 15 days of data had predicted consumptions at least as great as the biomass loss. Given the allowances made in the calculation of the predicted biomass it seems unlikely that this discrepancy can be accounted for by errors in biomass estimation or sampling errors in the extrusa material.

Some of the discrepancy may be explained if the fistula samples were taken early in the day when the rate of consumption of preferred species was higher than for the day as a whole (i.e. before the biomass of the preferred species declined). The short collection periods are one of the major drawbacks of the oesophageal fistula technique. But this argument cannot explain all the discrepencies, and especially those late in the trials.

The sources of discrepency in the grazing trial data are difficult to determine and it is of little value discussing them further in this appendix. Despite Leigh & Mulham's contention that the percentage contribution of a species to the extrusa is a good indicator of the actual contribution to the diet, and that oesophageal fistula results "can play an important role in the quantitative estimation of the diet of grazing sheep", I decided that the results did not justify the increased problems of maintaining fistulated sheep in my grazing trials.

		Day					
JULY 1962		1	2	3	4	5	
grass	initial biomass	6.8	4.9	3.3	2.2	1.2	lb
	biomass loss	1.9	1.6	1.1	1.0	0.7	lb
	predicted consumption	3.7	1.8	0.6	0.3	0.1	lb
total biomass loss per head		3.0	2.6	1.6	1.4	0.7	lb hd^{-1}
AUGUST 1962							
grass	initial biomass	1.0	0.2	-	-		lb
	biomass loss	0.8	0.2	-	-		lb
	predicted consumption	6.4	0.6	0.5	0.6		lb
total biomass loss per head		4.4	3.1	2.8	2.2		lb hd^{-1}
FEBRUARY 1963							
grass	initial biomass	8.4	4.4	1.4	0.4	0.3	lb
	biomass loss	4.0	3.0	1.0	0.2	0.1	lb
	predicted consumption	4.0	2.8	0.4	0.4	0.4	lb
total biomass loss per head		2.8	2.0	1.2	0.9	0.8	lb hd^{-1}

Table A3.1. An analysis of the grass consumption in three trials carried out by Leigh & Mulham (1966a, b; 1967). The 'initial biomass' is the grass biomass at the beginning of the day; the 'biomass loss' is the loss of biomass during the period to the next biomass estimation; the 'predicted consumption' is calculated from the extrusa data assuming a 50% biomass loss due to trampling; and the 'total biomass loss per head' is calculated from the total biomass loss between estimates.

APPENDIX 4. (see section 7.42)

Assume that,

$$C = k * T / (\tau + g),$$

where, T is the total time spent grazing, τ is the mean search time, g the mean time to graze the forage found, and k is a constant (or, more correctly, the mean amount consumed in any act of consumption). The mean time spent searching between two separate consumptions of food, τ, can be estimated as follows. Assume that the sheep search at random with respect to the vegetation, therefore,

$$\tau \propto 1 / B.$$

The probability that the species encountered will be species i is proportional to b_i/B and the probability of it being consumed is $(b_i * \pi_i) / B$. Therefore, the mean probability of a successful encounter is $\Sigma (\pi_i * b_i) / B$. The mean number of encounters per successful encounter is $B / \Sigma (\pi_i * b_i)$, and the mean time between successful encounters is,

$$\tau = k' / \Sigma (\pi_i * b_i).$$

The mean amount consumed per encounter can be estimated as follows. The probability that the species consumed will be species i is, $\pi_i * b_i / \Sigma (\Pi_i * b_i)$ and therefore the mean consumption is,

$$k = \Sigma (\pi_i * b_i * w_i) / \Sigma (\pi_i * b_i).$$

If it is also assumed that the time spent grazing is proportional to the amount consumed, then the mean value of g is,

$$g = k'' * \Sigma(\pi_i * b_i * w_i) / \Sigma(\pi_i * b_i).$$

Therefore,

$$C = k * T / (\tau + g)$$

$$= \frac{T * \Sigma(\pi_i * b_i * w_i) / \Sigma(\pi_i * b_i)}{k' / \Sigma(\pi_i * b_i) + k'' * \Sigma(\pi_i * b_i * w_i) / \Sigma(\pi_i * b_i)}$$

$$= T * \Sigma(\pi_i * b_i * w_i) / (k' + k'' * \Sigma[\pi_i * b_i * w_i]),$$

and substituting $p_i = \pi_i * w_i$,

$$C = \alpha * T * \Sigma(p_i * b_i) / (1 + \beta * \Sigma[p_i * b_i]).$$

APPENDIX 5.

A listing of the GRZMOD2 program and its associated subroutines. The programs and subroutines used for the further analysis of the results are not listed in this thesis.

```
     DECK LISTING            750313

       PROGRAM GRZMOD2 (INPUT,OUTPUT,TAPE1=INPUT,TAPE2=OUTPUT,XXX,TAPE3=X
      1XX,DAT,TAPE4=DAT)
*    --- GRZMOD2 ---  MAIN PROGRAM FOR THE SHEEP PADDOCK SIMULATION.
       COMMON/CMAIN/NQ,NS,NG,DAY,ID,IDM,IM,ISEAS,IY,UTIME
       COMMON/MVAR/ SHEEP,ALW,AMET,WWOOL,WOOL,CONS(5),TCONS,ACONS(5),
      1 ATCONS,TRF,KRF,ATMEAND,EMET,SSHEEP
       COMMON/CGRAZE/ SALT(5),WATR(5),PREF(5),DIG(5),
      1 PWATI,PSALI,HUNG,CEFO,CONX,CONN,HUNGX,DFC,X1,X2,X3,TFC,H
       COMMON/CPAD/LSHADE(45),LCAMP(45),LWATPT,LA(2,8),LPOS(45),
      1 MAX,MXY,KSPEED
       COMMON/COUT/ ADRINK(24),KDRINK,BEH(37,6),TDRINK,DIST,BOUT(6)
       COMMON/CGROW/ EGS(37),EBS(37),TTE(37),TP(37),ON(37),
      1 BIOM(37,5)
       COMMON/CSUM/ WHT,Q1,Q4,Q5,Q6,ICC
       COMMON/CRAND/ ZZR,ZZT,ZZW,ZZZ
       COMMON /CGROWN/ MM1(37),MM2(37),IEGS(37),IEBS(37),
      1 GREGS,GREBS,DBEGS,DBEBS,LEGS,LEBS,LGEG,LGEB,XGRG,XGRB,TEX,
      2 DBEG,DBEB,ADG,ADB,TSD,ALT,BLT,TW,XGRA,XGRK,TPX,DBPA,DBPK,
      3 GRG,GRB,GRA,GRK,WP,WP2,WPC,ONLE,ONLP,TWG,TWB,TWK,TMG,TMB,TMK
       DIMENSION IWATPT(10),MESSG(8)
       DATA IWATPT/10*26/
       DATA IN,IO/1,2/
       ICC=1H1
       CALL DATE(KDT)
       CALL TIME(KTM)
       WHT=4.5
       Q1=3000.   $ Q5=10.
       CALL BLKDATA
       CALL SETDAY (60)
*    SET THE RANDOM NUMBER CORES.
       ZZZ=0.3687 $ ZZT=0.5137 $ ZZR=0.2824 $ ZZW=0.5138
       WRITE(2,2000) ZZR,ZZT,ZZW,ZZZ
  2000 FORMAT (*   RANDOM NUMBER CORES... */*   ZZR *F10.8*   ZZT *F10.8
      1 *   ZZW *F10.8*   ZZZ *F10.8)
       SHEEP=300.
*    SETTING UP
       CALL SETUP
       CALL PLOTIN
       NOD=90  $  NOP=30 $  NOW=5  $  NOS=1   $ NSUM=4
       NY=6
       IF(SHEEP.EQ.0.) NOS=0
       READ(IN,1000)   MESSG
  1000 FORMAT (8A10)
       WRITE(IO,2001) KDT,KTM,NOD,NOP,NOW,NSUM,MESSG
  2001 FORMAT (1H1,20X*GRAZING MODEL ...  RUN ON *A10,3X,A10,/
      1 *   NOD   NOP   NOW   NSUM*/,1X,4I6,/
      210X,8A10,//)
       CALL SUMMARY (2)

*    MAIN SIMULATION LOOP STARTS HERE.   -----------
       DO100I=1,NY
       LWATPT=IWATPT(I)
       CALL SHEAR (5, NOP,NOW,IO)
       CALL DAYSIM(NOD,NOP,NOW,NSUM,NOS,IO)
   100 CONTINUE
       CALL SHEAR (5 ,NOP,NOW,IO)
```

```
       CONTINUED

*   END OF MAIN SIMULATION LOOP.

*   FINISH OFF.
      CALL PAUPLOT (26HBLANK PAPER,BLACK INK,PLS. ,26)                         *
      CALL PLOTS (5HSB5IN,5)                                                   *
      CALL ENDSUM(2)                                                           *
      STOP
      END
```

```
    DECK LISTING           750313

     SUBROUTINE BLKDATA
*   SETS DATA STATEMENTS
*   THIS S/R COULD BE CONVERTED TO A BLOCKDATA  BY CHANGING THE S/R CARD.
     COMMON/CMAIN/NQ,NS,NG,DAY,ID,IDM,IM,ISEAS,IY,UTIME
     COMMON/MVAR/ SHEEP,ALW,AMET,WWOOL,WOOL,CONS(5),TCONS,ACONS(5),
    1 ATCONS,TRF,KRF,ATMEAND,EMET,SSHEEP
     COMMON/CWATVB/ SM(3,37),CP(3,37),TC(37),TSM(37),AK(3),Z(10),NZ
     COMMON/CGERM/ CWP,TCG,TCB,CG,CB,TTG(37),TTB(37)
     COMMON/CPAD/LSHADE(45),LCAMP(45),LWATPT,LA(2,8),LPOS(45),
    1 MXX,MXY,KSPEED
     COMMON/CSHPMV/ RESPMX,RESPH,AMETL,THIRST,DEHYD,TBMX,HCAP,DRINK,CFC
     COMMON/CHEAT/ PRESPA(20),HRCAMP(20),TBA(20),WATA(20),RESPA(20),
    1 HUNGA(20),ISTA(20),IPUSA(20),IXPA(20),IYPA(20),TFCA(20),
    2 TSURF,RESP,TBN,SOLAR,DAWN,DUSK,ALEN,RAD
     COMMON/CTEMP/ TMIN,TRANGE,TAIR,TMEAND,CPROB,KLEAR(24),
    1RF,VEL,IWS,IWDIR,EV
     COMMON/CGRAZE/ SALT(5),WATR(5),PREF(5),DIG(5),
    1 PWATI,PSALI,HUNG,CEFO,CONX,CONN,HUNGX,DFC,X1,X2,X3,TFC,H
     COMMON/CGROW/ EGS(37),EBS(37),TTE(37),TP(37),ON(37),
    1 BIOM(37,5)
     COMMON /CGROWK/ MM1(37),MM2(37),IEGS(37),IEBS(37),
    1 GREGS,GREBS,DBEGS,DREBS,LEGS,LEBS,LGEG,LGEB,XGRG,XGRB,TEX,
    2 DBEG,DBEB,ADG,ADB,TSD,ALT,BLT,TW,XGRA,XGRK,TPX,DBPA,DBPK,
    3 GRG,GRB,GRA,GRK,WP,WP2,WPC,ONLE,ONLP,TWG,TWB,TWK,TMG,TMB,TMK
     COMMON /CNIT/ OLIT(37),OSL(37),ONR,ONRA,ONRB,DECL
     COMMON/COUT/ ADRINK(24),KDRINK,BEH(37,6),TDRINK,DIST,BOUT(6)
     COMMON/CRAND/ ZZR,ZZT,ZZW,ZZZ
     COMMON/CSUM/ WHT,Q1,Q4,Q5,Q6,ICC

*   DATA    ---------------------
     DATA NQ,NS,NG,DAY,ID,IDM,IM,ISEAS,IY,UTIME/                       CMAIN
    1 37,5,10,1.,1,1,1,1,1,1.0/

     DATA SHEEP,ALW,AMET,WWOOL,WOOL/                                   MVAR
    1 300.,40., 80.,.1,.0045/
     DATA ACONS,ATCONS,TRF,ATMEAND,KRF/8*0.,0/

     DATA SM/37*(10.,25.,25.)/                                         CWATVB
     DATA AK/.7,.2,.1/,NZ/3/
     DATA Z/.01,.02,.03,.04,.05,.1,.25,.4,.6,.8/
     DATA TC,TSM/37*138.,37*60./
     DATA CP/37*(23.,57.5,57.5)/

     DATA TCG,TCB,CG,CB,CWP,TTG,TTB/                                   CGERM
    1 20.,0.,200.,1350.,10.,37*0.,37*0./

     DATA LSHADE/6,7,3,4,5,6,7,8,9,10,16,17,17,14,15,16,17,23,23,14,21,  CPAD
    122,23,23,29,26,27,28,29,29,31,27,33,28,29,36,36,38,44,44,36,42,43,
    244,44/
     DATA LCAMP/6,6,9,9,9,6,6,9,9,9,6,6,9,9,9,26,26,24,28,28,26,26,28,2
    16,28,26,26,26,28,26,36,26,28,28,44,36,36,44,44,44,36,36,44,44,44/
     DATA LWATPT,LA/26,   -1,-1,-1,0,-1,1,0,1,1,1,1,0,1,-1,0,-1/
     DATA LPOS/ 6,7,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,19,21,2
    12,23,24,24,26,27,28,29,29,31,32,33,34,34,36,37,38,39,39,41,42,43,4
    24,44/
     DATA MXX,MXY,KSPEED/ 5,9,2/
```

```
 CONTINUED

DATA RESPMX,RESPH,AMETL,THIRST,DEHYD,TBMX,HCAP,DRINK,CFC /         CSHPMV
1     300.0 ,200. ,60. ,1000. ,  0. , 42., 30.,4000.,0.20/

DATA PRESPA,HRCAMP,TBA,WATA,HUNGA,ISTA,IPOSA,IXPA,IYPA,TFCA/       CHEAT
1 20*80., 20*19., 20*40., 20*3000., 20*0.6 , 20*3, 20*20,
2 20*1, 20*6, 20*0./
DATA ALEN ,RAD,TBN/0.6,0.2,40./

DATA TMIN,TRANGE/ 8.0,15.0/                                        CTEMP

DATA SALT/10.,40.,25.,160.,110./                                   CGRAZE
DATA WATR/1700.,2600.,1000.,1700.,2600./
DATA FREF/ 3.0,1.25,0.5,1.0,0.1/
DATA DIG/0.7,0.6,0.3,0.8,0.7/
DATA CONX, HUNGX ,H, X2, X3 /
1 .25 , 0.75 , 0.90 , 0.0046 , 0.40 /

DATA GREGS  ,GREBS  ,DBEGS  ,DBEBS  ,LEGS   ,LEBS   ,LGEG   ,      CGROWK
1     LGEB   ,XGRG   ,XGRB   ,TEX    ,DBEG   ,DBEB   ,ADG    ,
2     ADB    ,TSD    ,ALT    ,BLT    ,XGRA   ,XGRK   ,TPX    ,
3     DBPA   ,DBPK   ,TW     ,WPC    ,  ONLE  ,ONLP   /
4     1.4    ,1.4    ,0.8    ,0.8    ,7      ,7      ,21     ,
5     14     ,0.08   ,0.05   ,1500.  ,0.0008 ,0.0008 , 0.5   ,
6     0.3    ,1.0    ,0.005  ,0.002  ,0.0083 ,0.006  ,1500.0   ,
7    0.00014 ,0.00010,0.010   ,   0.2   ,   0.5  ,   0.5   /
DATA WP,WP2/10.,25./
DATA  TWG   ,  TWB   ,  TWK   ,  TMG   ,  TMB   ,  TMK   /
1      0.01 ,  0.01,0.0016 , 23.0 ,  22.0  ,  25.0   /

DATA ONRA,ONRB,DECL/0.5,1.0,0.0089/                                CNIT
DATA OLIT,OSL/37*4.,37*20./

DATA ADRINK,KDRINK/24*0.,0/                                        COUT
DATA BER/222*0./
DATA ZZZ,ZZR,ZZT,ZZW/ 0.321,0.564,0.789,0.147/                              *
DATA Q1,Q4,Q5,Q6/2000.,  0.5,  12.0,  3.0 /,WHT/6.0/
RETURN
END
```

```
    DECK LISTING           750313

       SUBROUTINE CENTRE (A,CX,CY,SS,IO)
*     CALCULATES THE CENTRE POINT OF A DISTRIBUTION OF VALUES IN WERTIGO.
*     THE CENTRE POINT IS DEFINED AS THE POINT WITH THE MINIMUM SQUARED
*     DISTANCE TO THE OTHER POINTS.
*     A IS THE ARPAY OF DATA (37 CELLS).
*     CX AND CY ARE THE CO-ORDS OF THE POINT (THE S-W CORNER CELL IS 1,1).
*     SS IS THE MEAN OF THE SQUARED DISTANCES.

       DIMENSION A(37),VEC(2,37)
       INTEGER VEC
       DATA VEC/3,9,4,9,5,9, 1,8,2,8,3,8,4,8,5,8, 1,7,2,7,3,7,4,7,5,7,
      1 1,6,2,6,3,6,4,6, 1,5,2,5,3,5,4,5, 1,4,2,4,3,4,4,4, 1,3,2,3,3,3,4,
      23, 1,2,2,2,3,2,4,2, 1,1,2,1,3,1,4,1/
       CX=CY=SS=T=0.
       DO10I=1,37
       T=T+A(I)
       CX=A(I)*VEC(1,I)+CX
    10 CY=A(1)*VEC(2,I)+CY
       IF(T.EQ.0.) GO TO 100
       CX=CX/T
       CY=CY/T
       DO20I=1,37
       DX=VEC(1,I)-CX
       DY=VEC(2,I)-CY
    20 SS=SS+(DX*DX+DY*DY)*A(I)
       SS=SS/T
       IF(IO.NE.0) WRITE(IO,2000) CX,CY,SS
  2000 FORMAT (*   CENTRE POINT OF THE WERTIGO DISTRIBUTION *2F6.2* S.SQ.*
      1*F9.3)
   100 RETURN
       END
```

```
      DECK LISTING            750313

      SUBROUTINE DAYSIM (NOD,NOP,NOW,NSUM,NOS,IO)
*     S/R EXECUTES NOD DAYS OF SIMULATION, CALLING A PLOTTING ROUTINE ON EVERY
*      NOP CALL. A SUMMARY IS THEN PRINTED, AND THIS PROCESS IS REPEATED
*     NSUM TIMES.
*     IF NOS=0 THEN NO SHEEP ARE SIMULATED.
*     IO IS THE OUTPUT TAPE.

      COMMON/CMAIN/NQ,NS,NG,DAY,ID,IDM,IM,ISEAS,IY,UTIME
      COMMON/MVAR/ SHEEP,ALW,AMET,WWOOL,WOOL,CONS(5),TCONS,ACONS(5),
     1 ATCONS,TRF,KRF,ATMEAND,EMET,SSHEEP
      COMMON/CTEMP/ TMIN,TRANGE,TAIR,TMEAND,CPROB,KLEAR(24),
     1RF,VEL,IWS,IWDIR,EV
      COMMON/CWATVB/ SM(3,37),CP(3,37),TC(37),TSM(37),AK(3),Z(10),NZ
      COMMON/CGROW/ EGS(37),EBS(37),TTE(37),TP(37),ON(37),
     1 BIOM(37,5)
      COMMON /CGROWK/ MM1(37),MM2(37),IEGS(37),IEBS(37),
     1 GREGS,GREBS,DBEGS,DBEBS,LEGS,LEBS,LGEG,LGEB,XGRG,XGRB,TEX,
     2 DBEG,DBEB,ADG,ADB,TSD,ALT,BLT,TW,XGRA,XGRK,TPX,DBPA,DBPK,
     3 GRG,GRB,GRA,GRK,WP,WP2,WPC,ONLE,ONLP,TWG,TWB,TWK,TMG,TMB,TMK
      COMMON/PLOT1/ YO(6),YS(6),KH(6),NP1,NTAPE,INC,LWD
      COMMON/COUT/ ADRINK(24),KDRINK,BEH(37,6),TDRINK,DIST,BOUT(6)
      DIMENSION CONSA(5)
      DIMENSION  MNTH(12),DAYL(12)
      DATA YO/6*0./, YS/5*10.0,0.05/
      DATA KH/1RG,1RB,1RS,1RA,1RE,1RN/
      DATA NP1,NTAPE,INC,LWD/6,3,10,100/
      DATA MNTH/31,28,31,30,31,30,31,31,30,31,30,31/
      DATA DAYL/14.1,13.2,12.3,11.3,10.4,9.9,10.2,10.9,11.9,12.9,13.8,14.4/
     1.4/
      DATA IS,IP,HR,WDIST,DRINK,GTM/4,1,1.,0.,0.,0./
      DATA DY,IDP/1.,0/
      DATA CONSA/5*0./

*     EVAPORATION FUNCTION.
      EVAP(X,J)=-6.618+0.125*X+0.654*DAYL(J)
      W=0.

*     LOOP FOR NUMBER OF SUMMARIES.
      DO30ISM=1,NSUM
      CALL SECOND (W1)

*     LOOP FOR NOD DAYS.
      DO20I=1,NOD
*     TIME KEEPING
      ID=ID+1
      DAY=DAY+1.0
      DY=DY+1.
      IDM=IDM+1
      IF(IDM.LE.MNTH(IM)) GO TO 10
      IM=IM+1
      IDM=1
      ISEAS=MOD(IM/3,4)+1
      IF(IM.LE.12) GO TO 10
      IY=IY+1
      IM=1
      DY=1.
```

```
      CONTINUED

*     EXECUTE ONE DAY OF THE SIMULATION.
   10 RF=RFALL(IM)
      CALL WIND (ISEAS)
      CALL TEMPER(HR)
      TRF=TRF+RF
      IF(RF.GT.0.) KRF=KRF+1
      ATMEAND=ATMEAND+TMEAND
      EV=EVAP(TMIN+TRANGE,IM)
      CALL WATVB (RF,EV)
      CALL GROW
      IF(NOS.EQ.0) GO TO 15
      CALL SHPMV
      CALL SHPHYS
   15 CONTINUE

*     PLOT IF WANTED.
      KKKM=0
      IF(MOD(ID,NOP).EQ.0)
     1          CALL PLOTTER (DAY,BOUT(1),BOUT(2),BOUT(3),BOUT(4),              *
     2                        BOUT(5),ON(IP),KKKM)                              *

*     GATHER DATA FOR OUTPUT ON TO MASS STORAGE DEVICE.
      ARF=ARF+RF
      TX=TMIN+TRANGE+TX
*     IS IT TO BE WRITTEN ON THIS RUN.
      IF(NOW.EQ.0) GO TO 20
*     CALCULATE MEAN VALUES ETC.
      EMETS=EMETS+EMET
      ACCONS=TCONS+ACCONS
      DO170II=1,5
  170 CONSA(II)=CONSA(II)+CONS(II)
      IF(MOD(ID,NOW).NE.0) GO TO 20
      TTG=NOW
      TG=NG*NOW
      TTGX=ID-IDP
      IDP=ID
      WDIST=(DIST-WDIST)/TG
      DRINK=(TDRINK-DRINK)/TG
      SM1=SM2=SM3=SON=AGTM=0.
      DO180II=1,NQ
      SM1=SM1+SM(1,II)
      SM2=SM2+SM(2,II)
      SM3=SM3+SM(3,II)
      SON=SON+ON(II)
  180 AGTM=AGTM+BEH(II,1)
      GTM=(AGTM-GTM)/TG
      TX=TX/TTGX
      ARF=ARF/TTGX
      SM1=SM1/NQ
      SM2=SM2/NQ
      SM3=SM3/NQ
      SON=SON/NQ
      EMETS=EMETS/(TG*20000.)
      ACCONS=ACCONS/TTG
      DO190II=1,5
  190 CONSA(II)=CONSA(II)/TTG
*     WRITE DATA ON TO FILE <<IS>>
      WRITE(IS) DAY,DY,ACCONS,TX,ARF,WOOL,EMETS,DRINK,WDIST,GTM,ALW,BOUT
```

```
      CONTINUED

     1(6),SM1,SM2,SM3,SON,(BOUT(II),II=1,5),(CONSA(II),II=1,5)
*   RESET THE PARAMETERS FOR THE NEXT ACCUMULATION.
      ACCONS=EMETS=TX=ARF=0.
      WDIST=DIST
      DRINK=TDRINK
      GTM=AGTM
      DO195II=1,5
  195 CONSA(II)=0.
   20 CONTINUE
*   END OF DAY LOOP   -------------------------

*   PRODUCE THE SUMMARY.
      CALL SECOND (W2) $ W=W2-W1+W
      CALL SUMMARY(IO)
      WDIST=DRINK=GTM=0.
   30 CONTINUE
*   END OF SUMMARY LOOP   -----------------

      W=W/(NOD*NSUM)
      WRITE(IO,2000) W
 2000 FORMAT (*   MEAN TIME PER DAY OF SIMULATION *F6.3 * SECS.*)
      RETURN

      ENTRY SETDAY
*   THIS SECTIONS DOES THE TIME INITIALIZATION FOR A START FROM ANY DAY OF THE
*   YEAR. THE DEFAULT IS JAN 1.
*   USE AS  CALL SETDAY (N) WHERE N IS THE NUMBER OF THE DAY IN THE YEAR.
      IDM=0
      DO110I=1,12
      IDM=IDM+MNTH(I)
      IF(NOD.LE.IDM) GO TO 120
  110 CONTINUE
      NOD=1
      IDM=31
  120 IM=I
      DAY=NOD
      DY=DAY
      IDM=NOD-IDM+MNTH(I)
      IY=1
      ISEAS=MOD(IM/3,4)+1
      RETURN
      END
```

DECK LISTING   750313

```
      SUBROUTINE GERM (N,KF1,KF2)
*    EPHEMERAL GERMINATION  --  CALLED FROM  GROW.        CHAPT 6.
      COMMON/CGERM/ CWP,TCG,TCB,CG,CB,TTG(37),TTB(37)
      COMMON/CWATVB/ SM(3,37),CP(3,37),TC(37),TSM(37),AK(3),Z(10),NZ
      COMMON/CTEMP/ TMIN,TRANGE,TAIR,TMEAND,CPROB,KLEAR(24),
     1PF,VEL,IWS,IWDIR,EV
      TE=TMIN-TRANGE
      KF1=KF2=0
*    IS THERE ENOUGH WATER FOR GERMINATION.
      IF(SM(1,N).GT.CWP) GO TO 10
      TTG(N)=0.
      TTB(N)=0.
      RETURN
*    ACCUMULATE <<DEGREE DAYS> AND SET FLAGS <<KF1 AND KF2>> IF GERMINATION
*          HAS OCCURRED.
   10 TB=AMAX1(TE-TCB,0.)
      IF(TTB(N).GE.CB) GO TO 20
      IF(TTB(N)+TB.LT.CB) GO TO 20
      KF2=1
   20 TG=AMAX1(TE-TCG,0.)
      IF(TTG(N).GE.CG) GO TO 30
      IF(TTG(N)+TG.LT.CG) GO TO 30
      KF1=1
   30 TTG(N)=TTG(N)+TG
      TTB(N)=TTB(N)+TB
      RETURN
      END
```

```
      DECK LISTING           750313

      SUBROUTINE GRAZE (IPOS,IG)
*   MODEL OF PLANT CONSUMPTION BY SHEEP.      CHAPT 7.
      COMMON/MVAR/ SHEEP,ALW,AMET,WWOOL,WOOL,CONS(5),TCONS,ACUNS(5),
     1 ATCONS.TRF.KRF,ATMEAND,EMET,SSHEEP
      COMMON/CMAIN/NQ,NS,NG,DAY,ID,IDM,IM,ISEAS,IY,UTIME
      COMMON/CGROW/ EGS(37),EBS(37),TTE(37),TP(37),ON(37),
     1 BIOM(37,5)
      COMMON/CGRAZE/ SALT(5),WATR(5),PREF(5),DIG(5),
     1 PWATI,PSALI,HUNG,CEFO,CONX,CONN,HUNGX,DFC,X1,X2,X3,TFC,H
      COMMON/CTGRZ/TGRZ(37)
      DIMENSION EFO(5)
      DIMENSION PEFO(20)
      DATA TGRZ/37*0./
      DATA PEFO/20*1./
      DATA AREA/64.0/

      TBIOM=0.0
      TFC=0.
      TEFO=0.0
*   CALC SHEEPG ...  SHEEP/HA.
      SHEEPG=SHEEP/(NG*AREA)
*   CALCULATE EFFECTIVE FORAGE.
      DO20I=1,NS
      TBIOM=TBIOM+BIOM(IPOS,I)
      EFO(I)=PREF(I)*BIOM(IPOS,I)
   20 TEFO=TEFO+EFO(I)
*      CALCULATE TOTAL FORAGE CONSUMPTION.       (FC)
      IF(TEFO.LE.0.0) RETURN
      PF=AMIN1(TEFO/PEFO(IG),1.0)
      PEFO(IG)=TEFO
      FC=CONX*X2*TBIOM/(1.0+X2*TBIOM)
      FC=FC*PF*(1.0/(1+HUNG))
      TGRZ(IPOS)=TGRZ(IPOS)+FC*SHEEPG
*   DISTRIBUTE FC AMONG THE SPECIES.
      DO30I=1,NS
      C=AMIN1(FC*EFO(I)/TEFO, BIOM(IPOS,I)/SHEEPG)
      TFC=TFC+C
      BIOM(IPOS,I)=BIOM(IPOS,I)-C*SHEEPG
      PSALI=PSALI+C*SALT(I)
      PWATI=PWATI+C*WATR(I)
   30 CONS(I)=CONS(I)+C
*   CALCULATE THE NEW HUNGER.
      HUNG=HUNG+TFC
      RETURN
      END
```

```
    DECK LISTING            750313

      SUBROUTINE GROW
*    PLANT GROWTH SUBMODEL        CHAPT 6.
      COMMON/CMAIN/NQ,NS,NG,DAY,ID,IDM,IM,ISEAS,IY,UTIME
      COMMON/CTEMP/ TMIN,TRANGE,TAIR,TMEAND,CPROB,KLEAR(24),
     1RF,VEL,IWS,IWDIR,EV
      COMMON/CWATVB/ SM(3,37),CP(3,37),TC(37),TSM(37),AK(3),Z(10),NZ
      COMMON/CGROW/ EGS(37),EBS(37),TTE(37),TP(37),ON(37),
     1EG(37),EB(37),ESD(37),PA(37),PK(37)
      COMMON /CGROWK/ MM1(37),MM2(37),IEGS(37),IEBS(37),
     1 GREGS,GREBS,DBEGS,DBEBS,LEGS,LEBS,LGEG,LGEB,XGRG,XGRB,TEX,
     2 DBEG,DBEB,ADG,ADB,TSD,ALT,BLT,TW,XGRA,XGRK,TPX,DBPA,DBPK,
     3 GRG,GRB,GRA,GRK,WP,WP2,WPC,ONLE,ONLP,TWG,TWB,TWK,TMG,TMB,TMK
      COMMON/CNIT/ OLIT(37),OSL(37),ONR,ONRA,ONRB,DECL
      COMMON/COUT/ ADRINK(24),KDRINK,BEH(37,6),TDRINK,DIST,BOUT(6)

      TE=TMEAND
      DO10I=1,6
   10 BOUT(I)=0.

*    NITRIFICATION
      DO250N=1,NQ
      IF(RF.LE.1.0.AND.SM(1,N).LE.18.0) GO TO 50
      IF(OSL(N).LE.0.4) GO TO 50
      ON(N)=ON(N)+0.4
      OSL(N)=OSL(N)-0.4
      TW=TW+0.4
   50 UU=0.
      ONR=AMAX1(AMIN1(ONRB*(ON(N)-ONRA),1.0),0.0)
*     SET VARIOUS PARAMETERS DESCRIBING THE SOIL MOISTURE STATUS.
      MM1(N)=MM1(N)+1
      MM2(N)=MM2(N)+1
      IF(SM(1,N).LT.WP) MM1(N)=0
      IF(SM(2,N).LT.WP2)MM2(N)=0
      M1=MM1(N)
      M2=MM2(N)

*     SEEDLING SECTION
      IF(EGS(N).EQ.0.) GO TO 110
      GR=GREGS
      EGS(N)=EGS(N)*GR
      IEGS(N)=IEGS(N)+1
*     GRASS SEEDLINGS
      IF(IEGS(N).LT.LEGS) GO TO 110
*     MATURES
      IF(M1.EQ.0) GR=DBEGS
      EG(N)=EG(N)+EGS(N)
      EGS(N)=0.

*     BASSIA SEEDLINGS
  110 IF(EBS(N).EQ.0.) GO TO 120
      IEBS(N)=IEBS(N)+1
      GR=GREBS
      IF(M1.EQ.0) GR=DBEBS
      EBS(N)=EBS(N)*GR
      IF(IEBS(N).LT.LEBS) GO TO 120
*     MATURE
      EB(N)=EB(N)+EBS(N)
```

```
      CONTINUED

      EBS(N)=0.

*   GERMINATION
  120 CALL GERM (N,KF1,KF2)
      IF(KF1.EQ.0) GO TO 130
      EGS(N)=5.0
      IEGS(N)=0
  130 IF(KF2.EQ.0) GO TO 140
      EBS(N)=5.0
      IEBS(N)=0

*   EPHEMERAL GROWTH
  140 IF(M1.EQ.0) GO TO 150
      IF(ONR.LE.0.) GO TO 160
*   GROWTH - GRASS
      A=AMAX1(1.0-TWG*(TMG-TE)**2,0.0)
      AA=1.0
      GRG=XGRG*A*AA*(1.0-TTE(N)/TEX)*ONR
      EG(N)=EG(N)*(1.0+GRG)
*   GROWTH -- BASSIA
      A=AMAX1(1.0-TWB*(TMB-TE)**2,0.0)
      AA=1.0
      GRB=XGRB*A*AA*(1.0-TTE(N)/TEX)*ONR
      EB(N)=EB(N)*(1.0+GRB)
      OO=(GRG*EG(N)+GRB*EB(N))*0.015
      GO TO 160

*   DIE BACK OF EPHEMERALS
  150 GRG=-DBEG*TE
      GRB=-DBEB*TE
      EG(N)=AMAX1(EG(N)-ADG,0.0)*(1.0+GRG)
      EB(N)=AMAX1(EB(N)-ADB,0.0)*(1.0+GRB)
      ESD(N)=ESD(N)-(EG(N)*GRG+EB(N)*GRB)*TSD
*   DECAY OF STANDING DEAD
  160 T=ALT+BLT*RF
      ESD(N)=ESD(N)*(1.0-T)
      OLIT(N)=OLIT(N)+ESD(N)*T*0.015/TSD

*   PERENNIAL GROWTH
*   ATRIPLEX VESICARIA
      IF(M1.LT.4) GO TO 170
      IF(ONR.LE.0.) GO TO 200
      A=AMAX1((0.166+0.0206*TE+8.245/(TE-59.0))/0.6,0.0)
      AA=AMAX1(AMIN1(WPC*(SM(2,N)-WP2),1.0),0.1)
      GRA=XGPA*A*AA*(1.0-TP(N)/TPX)*ONR
      PA(N)=PA(N)*(1.0+GRA)
      OO=PA(N)*GRA*0.023+OO
      GO TO 180
  170 IF(M2.NE.0) GO TO 180
      GRA=-DBPA*TE
      PA(N)=PA(N)*(1.0+GRA)
      OLIT(N)=OLIT(N)-PA(N)*GRA*0.023

*   KOCHIA SEDIFOLIA
  180 IF(M1.LT.4) GO TO  190
      A=AMAX1(1.0-TWK*(TMK-TE)**2,0.0)
      AA=(AMAX1(SM(2,N)-WP2,0.)+AMAX1(SM(3,N)-WP2,0.))/2.0
      AA=AMAX1(AMIN1(WPC*AA,1.0),0.1)
```

```
       CONTINUED


      GRK=XGRK*A*AA*(1.0-TP(N)/TPX)*ONR
      PK(N)=PK(N)*(1.0+GRK)
      OO=PK(N)*GRK*0.08+OO
  190 IF(M2.GE.0.OR.SM(3,N).GE.WP2) GO TO 200
      GRK=-DBPK*TE
      PK(N)=PK(N)*(1.0+GRK)
      OLIT(N)=OLIT(N)-PK(N)*GRK*0.08

*    END
  200 ON(N)=ON(N)-OO
*    LITTER BREAKDOWN.
      T=OLIT(N)*DECL
      OLIT(N)=OLIT(N)-T
      OSL(N)=OSL(N)+T
*    GATHER VARIOUS SUMMARY PARAMETERS.
      TTE(N)=EGS(N)+EG(N)+EBS(N)+EB(N)+ESD(N)
      TP(N)=PA(N)+PK(N)
      BOUT(1)=BOUT(1)+EG(N)
      BOUT(2)=BOUT(2)+EB(N)
      BOUT(3)=BOUT(3)+ESD(N)
      BOUT(4)=BOUT(4)+PA(N)
      BOUT(5)=BOUT(5)+PK(N)
  250 CONTINUE
      DO300I=1,5
      BOUT(I)=BOUT(I)*0.064
  300 BOUT(6)=BOUT(6)+BOUT(I)
      RETURN
      END
```

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     DECK LISTING           750313

      SUBROUTINE HEAT (IG,HR)
*    CALCULATES THE HEAT BALANCE FOR A STANDARD SHEEP
*           UNITS:::WATTS, METERS, SECONDS, CELCIUS.
*           ALBEDO(WOOL)=0.40. ALBEDO(SOIL)=0.25, WOOL CONDUCTIVITY=0.064W/M**2 C

      COMMON/CMAIN/NQ,NS,NG,DAY,ID,IDM,IM,ISEAS,IY,UTIME
      COMMON/MVAR/ SHEEP,ALW,AMET,WWOOL,WOOL,CONS(5),TCONS,ACUNS(5),
     1 ATCONS,TPF,KRF,ATMEAND,EMET,SSHEEP
      COMMON/CHEAT/ PRESPA(20),HRCAMP(20),TBA(20),WATA(20),RESPA(20),
     1 HUNGA(20),ISTA(20),IPOSA(20),IXPA(20),IYPA(20),TFCA(20),
     2 TSURF,RESP,TBN,SOLAR,DAWN,DUSK,ALEN,RAD
      COMMON/CTEMP/ TMIN,TRANGE,TAIR,TMEAND,CPROB,KLEAR(24),
     1RF,VEL,IWS,IWDIR,EV
      DATA PDAY,SINLAT  ,CUSLAT  ,TANLAT  ,SOLCON/
     1       -1.,-0.54464,0.83867 ,-0.6494  ,1360.0/
      DATA ABSCON/0.9/

      RESF(HT,T8)=(((HT+AM+B*T8)/T-TB)*BB+AMET)/R

      IF(DAY.EQ.PDAY) GO TO 10
*    SET UP CALCULATION FOR A NEW DAY.
      PDAY=DAY
      DEC= 0.4101*COS(0.017214*(DAY-172.0))
      A=3.82*ACOS(-TANLAT*TAN(DEC))
      DAWN=12.3-A
      DUSK=12.3+A
      SD=SIN(DEC)*SINLAT
      CD=COS(DEC)*COSLAT
      RADW=RAD+WOOL
      BB=RADW*ALEN*B
      A=25.4*(VEL*RADW)**0.805/RAD
      B=0.402/WOOL
      T=A+B+23.1
      AMET=6.4*ALW**0.75
      IF(IG.EQ.0) RETURN

*    SET UP CALCULATION FOR A NEW HOUR.
   10 HA=-0.2618*(HR-11.8)
      SAL=CD*COS(HA)+SD
      HT1=0.
      HT2=0.
*   SUN BELOW THE HORIZON
      IF(SAL.LE.0.0) GO TO 40
      AM=1.0/SAL
      SOLAR=SAL*SOLCON*ABSCON**AM
      IHR=HR
      IF(KLEAR(IHR).EQ.0) GO TO 20
*    SUNNY
      HT1=0.18*SOLAR
      HT2=1.90*SOLAR
      GO TO 40
*    CLOUDY
   20 HT1=0.05*SOLAR
      HT2=0.74*SOLAR
   40 AM=(28.7+A)*TAIR-357.
      R=0.58-0.0053*TAIR
      RES1=RESF(HT1,TBN)
```

```
       CONTINUED


      RES2=RESF(HT2,TBN)
      RETURN

C   RETURNS RESPIRATION RATE.
      ENTRY RESPRT
      I=ISTA(IG)
      IF(I.EQ.2.OR.I.EQ.3) GO TO 50
      RESP=RES2
      IF(TBA(IG).EQ.TBN) GO TO 60
      RESP=RESF(HT2,TBA(IG))
      GO TO 60
   50 RESP=RES1
      IF(TBA(IG).EQ.TBN) GO TO 60
      RESP=RESF(HT1,TBA(IG))
   60 RESPA(IG)=RESP
      RETURN
      END
```

```
    DECK LISTING            750313

      SUBROUTINE MAP (AR,AMN,AMX,LAB,KC)
*    PRINTS UP TO 12 MAPS OF WERTIGO ACROSS A PAGE. EACH MAP IS 10 X 12 CHAR.
*    ALL MAPS SCALED BETWEEN AMN AND AMX AS 0,1,...  ..8,9,+
*    EACH CALL TO MAP ADDS 1 ARRAY, THE POSITIONING IS AUTOMATIC.
*      AR --- ARRAY(37)
*      AMN,AMX --- MIN AND MAX VALUES - IF EITHER IS -VE IT WILL BE SET AUTOMAT.
*      LAB --- A LABEL  R8 FORMAT
*      KC --- THE REPEAT CYCLE FOR AR.
*    ENTRY POINT  MAPDMP   PRINTS THE MAPS, USUALLY CALLED AS MAPDMP(0.)
*    IF AR≠0. THEN KTLIM SET TO AR(1).
*    INITIALLY KTLIM=12. IF A 13TH CALL TO MAP IS MADE WITHOUT A CALL TO MAPDMP,
*      THE MAPS ARE PRINTED AUTOMATICALLY.
      DIMENSION AR(37),KB(12,10),AN(12),AX(12),AT(12)
      DIMENSION IST(37,2)
      DATA KB/120*0/
      DATA KT,KTLIM,IO/0,12,2/
      DATA IST/3*2,5*3,5*4,4*5,4*6,4*7,4*8,4*9,4*10,
     1        12,6,0,24,18,12,6,0,24,18,12,6,0,6*(24,18,12,6)/
      DATA KN,KX,KTOT/5HORIG ,5HUNITS,5HTOTAL/
      IT=0
      KT=KT+1
*     IS A DUMP REQUIRED.
      IF(KT.LE.KTLIM) GO TO 10
      KTL=KTLIM
    5 WRITE(IO,2000) KB
      WRITE(IO,2001) KN,(AN(I),I=1,KTL)
      WRITE(IO,2001) KX,(AX(I),I=1,KTL)
      WRITE(IO,2001) KTOT,(AT(I),I=1,KTL)
      DO6I=1,120
    6 KB(I)=0
      IF(IT.EQ.1) GO TO 60
      KT=1
*     START SCALING.
   10 BMX=AMX
      BMN=AMN
      IF(BMN.GE.0..AND.BMX.GE.0.) GO TO 30
*     AUTO SCALING
      BMN=AR(1)
      BMX=AR(1)
      I=1
      DO20II=2,37
      I=I+KC
      BMN=AMIN1(BMN,AR(I))
   20 BMX=AMAX1(BMX,AR(I))
      IF(AMN.GE.0.) BMN=AMN
      IF(AMX.GE.0.) BMX=AMX
      R=0.
      IF(BMX.LE.BMN) GO TO 50
   30 CALL SCALE (BMN,BMX,10.,R,OR)                                                X*
      BMN=OR                                                                       X*
      IF(R.LE.0.) GO TO 50
      I=1-KC
      T=0.

*     SET UP MAP.
      DO40II=1,37
      I=I+KC
```

```
         CONTINUED


        T=T+AR(I)
        IV=INT((AR(I)-BMN)/R+0.5)+26
        IF(IV.LE.26) IV=1R.
        K=IST(II,1)
        KS=IST(II.2)
        IV=SHIFT(IV,KS)
     40 KB(KT.K)=KB(KT,K).OR.IV
     50 KB(KT,1)=LAB
        AN(KT)=BMN
        AX(KT)=P
        AT(KT)=T
        RETURN

*     FORCED PRINTING OF THE MAPS.
        ENTRY MAPDMP
        KTL=KT
        IF(KT.EQ.0) GO TO 60
        II=1
        GO TO 5
     60 IF(AR(I).NE.0.) KTLIM=AR(1)
        KT=0
        RETURN

   2000 FORMAT (5X,12R10)
   2001 FORMAT (2X,A5,12(2X,G8.3))
        END
```

```
    DECK LISTING           750313

      FUNCTION MOVE (IDEST,IST,IPOS,IXP,IYP)
*    CALCULATES THE POSITION OF A SUBFLOCK AS THEY MOVE TO A DESTINATION.
*    MOVE FROM IDEST TO IPOS VIA THE SHORTEST ROUTE.
*    MOVE ACROSS <<KSPEED>> CELLS PER HOUR.
      COMMON/COUT/ AURINK(24),KDRINK,BEH(37,6),TDRINK,DIST,BOUT(6)
      COMMON/CPAD/LSHADE(45),LCAMP(45),LWATPT,LA(2,8),LPOS(45),
     1 MXX,MXY,KSPEED
      DIMENSION LIST(3)
      DATA LIST/2,3,8/
      DATA KSPEED/2/

      K=0
      IF(IPOS.EQ.IDEST) GO TO 20
*    CALCULATE IDEST CO-ORDINATES.
      JYD=(IDEST-1)/MXX
      JXD=IDEST-JYD*MXX
      JYD=JYD+1
      XD=IXP-JXD
      YD=IYP-JYD

*    MAIN LOOP
   40 R=3.0
      IF(YD.EQ.0.0) GO TO 30
      R=ABS(XD/YD)
   30 IF(R.GT.0.44444445) XD=XD-SIGN(1.0,XD)
      IF(R.LT.2.25) YD=YD-SIGN(1.0,YD)
*    ARE THEY THERE YET.
      IF(XD.EQ.0..AND.YD.EQ.0.) GO TO 10
      IXP=JXD+XD
      IYP=JYD+YD
      K=K+1
*    IS THE HOUR UP YET.
      IF(K.LT.KSPEED) GO TO 40
      IPOS=(IYP-1)*MXX+IXP
      GO TO 50
*    ARRIVED.
   10 IXP=JXD
      IYP=JYD
      IPOS=IDEST
   20 IST=LIST(IST-4)
*    NEW POSITION  (STILL TRAVELLING).
   50 MOVE=IPOS
      DIST=DIST+SQRT(FLOAT(IABS(JXD-IXP)+IABS(JYD-IYP)))
      RETURN
      END
```

```
      DECK LISTING                 750313

      SUBROUTINE NUM (XA,LI,N)
*    USED BY S/R PLOTTER.
*    CONVERTS THE INTEGER PART OF XA TO AN IMAGE (1R  FORMAT ) IN  LI(N).
      DIMENSION LI(N)
      X=XA
      IF(X.EQ.0.0) GO TO 5
      DO1I=1,N
    1 LI(I)=1R
      L=ALOG10(X)
      IF(L+1.GT.N) GO TO 2
      I=N-L
      T=10.0**L
    4 LII=X/T
      LI(I)=LII+27
      X=X-LII*T
      I=I+1
      T=T/10.0
      IF(T.GE.1.0) GO TO 4
      RETURN
    2 DO3I=1,N
    3 LI(I)=1R*
      RETURN
    5 DO6I=1,N
    6 LI(I)=1R
      LI(N)=1R0
      RETURN $ END
```

```
      DECK LISTING           750313

      SUBROUTINE PLOTTER (X,YA,YB,YC,YD,YE,YF,KAR)

*    PRINTS LINE PRINTER PLOTS ON THE TAPE <<NTAPE>>.
*    PLOTS N≤6 VARIABLES (YA TO YF) ON A Y AXIS  <<LW>> CHARACTERS WIDE.
*    X INCREMENT ON EACH CALL IS <INC>> UNITS  -- THEY ARE PLOTTED ON CONSEC-
*          UTIVE LINES DOWN THE PAGE.
*    SCALE VALUES FOR YA TO YF ARE IN YO(6) AND YS(6)
*           YO - VALUE AT THE ORIGIN  ::  YS - THE INCREMENT PER COLUMN.
*    SYMBOLS FOR YA TO YF ARE IN KH(6).
*    KAR IS PRINTED UNDER R3 FORMAT ON EACH CALL. IT IS USEFUL FOR LABELLING
*        EVENTS.

      COMMON/PLOT1/ YO(6),YS(6),KH(6),N,NTAPE,INC,LW
      DIMENSION Y(6),LINE(130),LS(6)

      DATA LLL,LLE/1R-,1R:/
      Y(1)=YA $ Y(2)=YB $ Y(3)=YC $ Y(4)=YD $ Y(5)=YE $ Y(6)=YF

*    SET UP GRID
   13 KX=KX+1
      DO3I=1,LWB,2
    3 LINE(I)=LINE(I+1)=1R
      IF(KX.NE.INC) GO TO 5
      KX=0
      DO2I=11,LWA
    2 LINE(I)=1R-
      CALL NUM (X,LINE(3),6)
    5 LINE(10)=LINE(LWA+1)=LINE(9)=1R:
      LINE(30)=LINE(50)=LINE(70)=LINE(90)=1R.
      LK=LWC+1

*    SCALE THE VARIABLES.
      DO7I=1,N
    7 LS(I)=(Y(I)-YO(I))/YS(I)+10.5

*    SET UP THE LINE OF PLOTTING.

*    CHECK THAT THE POINT TO BE PLOTTED IN WITHIN RANGE AND DOES NOT COINCIDE
*                WITH ANOTHER POINT.
      DO8I=1,N
      IA=I $ KL=LK
      LINE(LK)=KH(I)
      LSI=LS(I)
      IF(LSI.GT.10000000) GO TO 8
      IF(LSI.GT.LWC) GO TO 12
      IF(LSI.LT.10) GO TO 14
*    CHECK FOR COINCIDENCE OF POINTS.
    9 IA=IA+1
      IF(IA.GT.6) GO TO 16
      DO17J=IA,6
      IF(LSI.NE.LS(J)) GO TO 9
      LS(J)=10000001
      LK=LK+1
      LINE(LK)=KH(J)
   17 CONTINUE
      GO TO 9
   16 IF(LK.EQ.KL) GO TO 15
```

```
      CONTINUED

      LINE(LK+1)=1R,
      LK=LK+2
      GO TO 15
*   POINT TOO LARGE FOR AXIS.
   12 LINE(LK)=1R↑
      LINE(LK+1)=KH(I)
      LINE(LK+2)=1R,
      LK=LK+3
      GO TO 8
*   POINT TOO SMALL FOR AXIS
   14 LINE(LK)=1R¬
      LINE(LK+1)=KH(I)
      LINE(LK+2)=1R,
      LK=LK+3
      GO TO 8
   15 LINE(LST)=KH(I)
    8 CONTINUE

*   WRITE THE LINE.
      IF(LINE(LK).NE.1R,) LINE(LK)=1R
      WRITE(NTAPE,101) KAR,(LINE(I),I=1,LK)
      RETURN

*   INITIALIZATION CALL - REQUIRES NO PARAMETERS.
*   IT SETS UP THE S/R FOR A PLOT OF THE SCALES AND SIZE GIVEN BY PLOT1.
      ENTRY PLOTIN
      LWA=LW+9
      LWB=LW+20
      LWC=LW+10
      LWW=LW-1
      LP=LW/20+1
      WRITE(NTAPE,103)
      KX=INC-1
*   PLOT AXIS LABELS.
      DO11I=1,N
      DO10J=1,LP
   10 Y(J)=YO(I)+(J-1)*20.0*YS(I)
      LS(1)=LS(2)=KH(I)
   11 WRITE(NTAPE,102) LS(1),LS(2),(Y(M),M=1,LP)
      RETURN

*   PRINTS AXIS LABELS AT THE END OF THE PLOT.
      ENTRY PLOTEND
      WRITE(NTAPE,105) (LLL,I=1,LWW),LLE
      DO18I=1,N
      DO19J=1,LP
   19 Y(J)=YO(I)+(J-1)*20.0*YS(I)
      LS(1)=LS(2)=KH(I)
   18 WRITE(NTAPE,102) LS(1),LS(2),(Y(M),M=1,LP)
      RETURN

*   RESETS THE CARRIAGE CONTROL PARAMETERS TO NORMAL (THEY WERE SET BY PLOTIN)
      ENTRY PLOTFIN
      WRITE(NTAPE,104)
      RETURN

  101 FORMAT (X,R3,X,130R1)
  102 FORMAT (*0*6X,2R1,2X,6(G11.4,9X))
```

```
      CONTINUED

  103 FORMAT (*0*/)
  104 FORMAT (* END*)
  105 FORMAT (13X*::*100R1)
      END
```

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      DECK LISTING          750313

      SUBROUTINE PRINTAB (ARR,L,M,N,IFM,IOTAPE,IOP)

*   PRINTS ARRAYS IN TABLE FORM, WITH VARIABLE FORMAT, FROM A SIMPLE S/R CALL:
*          CALL PRINTAB (ARR,5,3,1,4HF6.4,1)
*  WILL HANDLE 1 2 OR 3 DIMENSIONAL ARRAYS.
*
*   ARR -- THE ARRAY TO BE PRINTED                          *  N1         L
*   L,M,N --- THE DIMENSIONS IE ARR(L,M,N)                  *       1234567**
*   IFM --- FORMAT SECIFICATION FOR THE ENTRIES IN ARR      *      -----------
*      EG  F4.0 , F4.  , F4   , F10.0 , F10.  ,             *      1I
*          F10   , (OR G OR E)                              *      2I
*          I4  , I10  , (OR R OR A)                         *    M 3I
*   IOTAPE -- OUTPUT TAPE FOR THE TABLE                     *      4I
*          ERRORS PRINTED ON <<OUTPUT>>                     *      ↓I
*   NOTE::::: IF ISTOP=1 THEN THE PROGRAM WILL STOP ON      *  N2         L
*      ANY ERROR IT DETECTS, OTHERWISE ON DETECTING AN      *       1234567**
*      THE ATTEMPT TO PRINT THE TABLE IS ABANDONED          *      1I
*      AND THE PROGRAM CONTINUES.                           *      2I
*                                                           *    M 3I
*   THIS S/R REQUIRES THE S/R NUM, AND ALSO USES THE        *      4I
*      SYSTEMS ROUTINE KHAR AND KHIN.                       *      ↓I
*                                                           *    ETC
*   IOP --- IF IOP = 1   THE PROGRAM WILL AUTOMATICALLY TRANSPOSE THE L AND M
*      DIMENSIONS, AND RE-TRANSPOSE THEM BACK AGAIN BEFORE RETURNING.
*      THIS IS USEFUL FOR 2D MATRICES WHERE L IS MUCH GREATER THAN M.
*   NOTE::::: THIS OPTION WILL NOT WORK ON INTEGER DATA.
*

      DIMENSION ARR(L,M,N),IFORM1(3),IFORM2(3),LI(2)
      DATA IFORM1/10H(*0   N=*I ,10H2,/,5X,    ,10H(1X,I  ))   /
      DATA IFORM2/10H(1X,I4,   ,10H(1X,       ,2H)) /
      DATA ISTOP/0/

*   PUT L IN THE FORMAT STATEMENTS.
      LL=L
      IF(IOP.EQ.1) LL=M
      XL=LL
      CALL NUM(XL,LI,2)
      IF(LI(1).EQ.1R*) GO TO 50
      CALL KHIN (IFORM1(2),9,LI(1))
      CALL KHIN (IFORM1(2),10,LI(2))
      CALL KHIN (IFORM2(1),9,LI(1))
      CALL KHIN (IFORM2(1),10,LI(2))

*   PUT W (FROM FW.D EW.D GW.D IW AW RW) IN THE FORMAT STATEMENTS.
      K1=KHAR(IFM,2)
      K2=KHAR(IFM,3)
      IF(K1.GT.1R9.OR.K1.LT.1R0)GO TO 60
      CALL KHIN (IFORM1(3),6,K1)
      IF(K2.GT.1R9.OR.K2.LT.1R0)K2=1R
      CALL KHIN (IFORM1(3),7,K2)

*   PUT IFM IN THE FORMAT STATEMENTS.
      DO10I=1,6
      K1=KHAR(IFM,I)
      J=I+4
      CALL KHIN (IFORM2(2),J,K1)
```

```
        CONTINUED

   10 CONTINUE
*    CHECK THAT FIELD WIDTH IS NOT TOO GREAT.
      K=K1-27
      IF(K2.NE.1R ) K=K*10+K2-27
      K=LL*(K+1)+5
      IF(LL.GT.136) GO TO 40
*    PRINT THE TABLE.
      IF(IOP.EQ.1) GO TO 80
      DO20I=1,N
      WRITE(IOTAPE,IFORM1)I,(J,J=1,L)
      DO20J=1,M
   20 WRITE(IOTAPE,IFORM2) J,(ARR(II,J,I),II=1,L)
   30 RETURN
   80 DO90I=1,N
      WRITE(IOTAPE,IFORM1) I,(J,J=1,LL)
      DO90J=1,L
   90 WRITE(IOTAPE,IFORM2) J,(ARR(J,II,I),II=1,LL)

      GO TO 30
*    ERROR DIAGNOSTICS.
   40 PRINT1002,LL,IFM,IFORM1,IFORM2
      IF(ISTOP.EQ.1)70,30
   50 PRINT1000,LL
      IF(ISTOP.EQ.1) 70,30
   60 PRINT1001,IFM
      IF(ISTOP.NE.1) GO TO 30
   70 STOP 100
 1000 FORMAT (*0     ERROR IN <<PRINTAB>> .....*/*      L IS .GT.99 , L=*
     1I4)
 1001 FORMAT (*0     ERROR IN <<PRINTAB>> .....*/*      ERROR IN FORMAT SP
     1ECIFICATION *A10)
 1002 FORMAT (*0     ERROR IN <<PRINTAB>> .....*/*      FIELD TOO WIDE ---
     1 L= *I4* FORMAT SPECS. *A10,/*     FORMATS WERE::::*/5X,3A10,5X,3A10)
     110)
      END
```

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```
      SUBROUTINE PRINT1 (BIOM,DAY,KOP,IO)
*   PRINTS BIOMASS MAP FOR WERTIGO.
      DIMENSION BIOM(37,5)
      IF(KOP.EQ.1) GO TO 10
      WRITE(IO,8002)DAY
      GO TO 20
   10 WRITE(IO,8003) DAY
   20 WRITE(IO,8000) ((BIOM(I,J),I=1, 3),J=1,5),
     1               ((BIOM(I,J),I=4, 8),J=1,5),
     1               ((BIOM(I,J),I=9,13),J=1,5)
      WRITE(IO,8001) ((BIOM(I,J),I=14,17),J=1,5),
     1               ((BIOM(I,J),I=18,21),J=1,5),
     1               ((BIOM(I,J),I=22,25),J=1,5),
     1               ((BIOM(I,J),I=26,29),J=1,5),
     1               ((BIOM(I,J),I=30,33),J=1,5),
     1               ((BIOM(I,J),I=34,37),J=1,5)
      RETURN
 8000 FORMAT (/    ,5(11X,3F5.0),/    ,5(1X,5F5.0),/    ,5(1X,5F5.0))
 8001 FORMAT     (5(1X,4F5.0,5X))
 8002 FORMAT (*0*11X*GRASS*21X*BASSIA*16X*STANDING DEAD*11X*ATRIPLEX VES
     1ICARIA*9X*KOCHIA SEDIFOLIA*2X,F4.0)
 8003 FORMAT (1X,F5.0* NOT AVAILABLE*)
      END
```

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     DECK LISTING           750313

    FUNCTION RFALL (IM)

*        ::: MODIFIED GOODALL MODEL :::
    COMMON/CRAND/ ZZR,ZZT,ZZW,ZZZ
    DIMENSION TMA(4,2,12)
    DATA KP,B,C,SCALE/1,-0.0242,-0.045,0.254/
    DATA IFL,IP/0,0/

    DATA TMA/
   1.950,.961,.972,.989,.875,.888,.913,.963,.954,.963,.976,.986,.819,
   2.833,.889,.944,.958,.973,.982,.992,.813,.867,.907,.960,.943,.964,
   3.978,.992,.767,.796,.874,.961,.913,.942,.972,.992,.787,.860,.907,
   4.967,.899,.946,.972,.994,.753,.847,.900,.965,
   5.878,.931,.968,.995,.801,.885,.937,.995,.902,.939,.965,.995,.796,
   6.856,.928,.976,.906,.937,.962,.991,.851,.872,.915,.972,.926,.946,
   7.969,.993,.877,.886,.930,.965,.941,.954,.972,.988,.851,.883,.947,
   8.979,.948,.962,.977,.990,.855,.855,.880,.940/

    CALL RANGET (ZZZ)
    CALL RANSET (ZZR)
    IF(IM.EQ.IP) GO TO 3

*  SET UP FOR BEGINNING OF THE MONTH.
    IP=IM
    B=-0.021 $ C=-0.029 $ CC=0.58
    IF(IM.EQ.3) IFL=0
    IF(IM.LT.4.OR.IM.GT.9) GO TO 3
    B=-0.034 $ C=-0.049 $ CC=0.77
  3 IF(IM.NE.2.OR.IFL.EQ.1) GO TO 5

*  FEBRUARY TROPICAL CYCLONES.
    Z=RANF(0.0)
    IF(Z.GT.0.00177) GO TO 5
    RFALL=300.+400.*RANF(0.0)
    IFL=1
    GO TO 100
  5 Z=RANF(0.0)
    ZZ=RANF(0.0)
    DO10I=1,4
    IF(TMA(I,KP,IM).GT.Z) GO TO 20
 10 CONTINUE

*  FALLS GREATER THAN 0.50 INS.
    KP=2
    RFALL=ALOG(1.-ZZ)/B+50.
    GO TO 100

*  FALLS LESS THAN 50 PT.
 20 KP=2
    GO TO  (30,40,50,60) I
 30 RFALL=0.
    KP=1
    GO TO 100
 40 RFALL=Z7*9.0+0.5
    GO TO 100
 50 RFALL=ZZ*10.+10.
    GO TO 100
```

```
      CONTINUED

   60 RFALL=ALOG(1.-CC*ZZ)/C+20.

*    RESCALE THE RF TO THE APPROPRIATE UNITS  --  AND RESET RANF CORES.
  100 RFALL=RFALL*SCALE
      CALL RANGET (ZZR)
      CALL RANSET(ZZZ)
      RETURN
      END
```

0037704

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      SUBROUTINE SCALE (AMN,AMX,HT,SC,OR)
*   IAN NOBLE JULY 1974
*   CHOOSES SCALE FOR THE RANGE AMX TO AMN FOR AN AXIS OF LENGTH HT.
*   RETURNS,    SC -- INCREMEMENT PER UNIT LENGTH OF AXIS.
*               OR -- THE ORIGIN OF THE X AXIS.
*   SC IS CHOSEN TO BE 1.0,1.5,2.0,3.0,4.0,5.0,6.0, OR 8.0 TIMES 10.**N
*   OR IS THE BEST AVAILABLE WITHOUT REDUCING SCALE. IF POSSIBLE IT IS A
*     MULTIPLE OF 1.0, 0.5, 0.2 OR 0.1 OF SCALE.
*   OPERATES FOR ALL THE REAL NUMBER SCALE.

      DIMENSION C(4)
      DATA C/1.,2.,5.,10./
      R=(AMX-AMN)/HT
      IF(R.LE.0.) GO TO 80
   20 AL=ALOG10(R)
      IF(AL.LT.0.0) AL=AL-1.0
      AL=10.0**INT(AL)
      SC=R/AL
      IF(SC.GT.1.5) GO TO 30
      SC=1.5*AL
      GO TO 40
   30 SC=INT(SC+0.9999999)
      IF(SC.EQ.7.0.OR.SC.EQ.9.0) SC=SC+1.0
      SC=SC*AL
   40 AML=AMX-HT*SC
      BIAS=0.
      IF(AMN.GE.0.) GO TO 50
      BIAS=INT(-AMN/SC+1.0)*SC
      AML=AML+BIAS
      AMN=AMN+BIAS
   50 AL=AMN/SC
      DO60I=1,4
      OR=INT(C(I)*AL)*SC/C(I)
      IF(OR.GE.AML) GO TO 70
   60 CONTINUE
      OR=AMN
   70 AMN=AMN-BIAS
      OR=OR-BIAS
      RETURN
   80 IF(R.LT.0.) GO TO 90
      OR=AMN
      SC=1.0
      RETURN
   90 R=-R
      AL=AMX
      AMX=AMN
      AMN=AL
      GO TO 20
      END
```

```
    DECK LISTING            750313

      SUBROUTINE SETUP
*    SET INITIAL CONDITIONS
      COMMON/MVAR/ SHEEP,ALW,AMET,WWOOL,WOOL,CONS(5),TCONS,ACONS(5),
     1 ATCONS,TPF,KRF,ATMEAND,EMET,SSHEEP
      COMMON/CGROW/ EGS(37),EBS(37),TTE(37),TP(37),ON(37),
     1EG(37),EB(37),ESD(37),PA(37),PK(37)
      COMMON /CGROWK/ MM1(37),MM2(37),IEGS(37),IEBS(37),
     1 GREGS,GREBS,DBEGS,DBEBS,LEGS,LEBS,LGEG,LGEB,XGRG,XGRB,TEX,
     2 DBEG,DBEB,ADG,ADB,TSD,ALT,BLT,TW,XGRA,XGRK,TPX,DBPA,DBPK,
     3 GRG,GRB,GRA,GRK,WP,WP2,WPC,ONLE,ONLP,TWG,TWB,TMG,TMB
      COMMON/CRAND/ ZZR,ZZT,ZZW,ZZZ
      COMMON/CSUM/ WHT,Q1,Q4,Q5,Q6,ICC
      DIMENSION STPA(37),STPK(37)
      DATA DX/1.E-6/
      DATA STPA/170.,20.,110.,190.,150.,30.,80.,20.,290.,100.,280.,20.,2        *
     10.,160.,230.,130.,200.,90.,180.,190.,110.,0.,110.,180.,180.,300.,2       1*
     220.,290.,210.,430.,170.,50.,120.,320.,180.,80.,280./                      *
      DATA STPK/130.,200.,410.,150.,260.,140.,190.,320.,170.,360.,120.,         *
     1 270.,400.,250.,420.,280.,120.,290.,110.,260.,280.,600.,150.,220.,        *
     2 90.,110.,110.,60.,100.,290.,200.,230.,180.,190.,210.,30.,0./             *
      DO10I=1,37
      MM1(I)=MM2(I)=0
      IEBS(I)=IEGS(I)=0
      TP(I)=TTE(I)=0.0
      ON(I)=1.0
      EGS(I)=EBS(I)=0.
      EG(I)=EB(I)=50.
      ESD(I)=100.
      PA(I)=STPA(I)
      PK(I)=STPK(I)
   10 CONTINUE
      GRK=GRA=GRG=GRB=0.0
      SSHEEP=SHEEP
      CALL RANSET(ZZZ)
      RETURN

*       ENTRY BIOCH -- USED IN ENDSUM  (CHAPT 11.)
*    CALCULATES THE PERCENTAGE BIOMASS CHANGE AS A PERCENT OF THE TOTAL
*       PADDOCK CHANGE FOR THAT SPECIES.
      ENTRY BIOMCH
      Q=0.
      CALL WERTMP (PA,37,WHT,Q,Q,Q,4,19HA.VESICARIA BIOMASS,2HKG)
      Q=0.
      CALL WERTMP (PK,37,WHT,Q,Q,Q,4,19HK.SEDIFOLIA BIOMASS,2HKG)
      SSA=SEA=SSK=SEK=0.
      DO50I=1,37
      SSA=SSA+STPA(I)
      SEA=SEA+PA(I)
      SSK=SSK+STPK(I)
   50 SEK=SEK+PK(I)
      SSA=(SEA-SSA)/SSA
      SSK=(SEK-SSK)/SSK
      DO60I=1,37
      EG(I)=(PA(I)-STPA(I))/((STPA(I)+DX)*SSA)-1.0
      IF(STPA(I).EQ.0.) EG(I)=0.
      PA(I)=ABS(EG(I))
      EB(I)=(PK(I)-STPK(I))/((STPK(I)+DX)*SSK)-1.0
```

```
       CONTINUED

      IF(STPK(I).EQ.0.) EB(I)=0.
   60 PK(I)=ABS(EH(I))
      WRITE(2,2000) EG,EB
 2000 FORMAT (3(2X,12F8.3,/),F8.3)
      Q=0.
      CALL WERTMP (PA,37,WHT,Q,Q,Q,4,18HA.VESICARIA CHANGE,1H )
      Q=0.
      CALL WERTMP (PK,37,WHT,Q,Q,Q,4,18HK.SEDIFOLIA CHANGE,1H )
      RETURN
      END
```

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    DECK LISTING           750313

     SUBROUTINE SHEAR (NOD,NOP,NOW,IO)
*   SHEEP ARE SHORN - IE WOOL IS REDUCED TO 0.1 KG AND 2.0 MM.
*   TAKES NOD DAYS - SHEEP MAINTAIN LIVEWEIGHT
*   RE-ENTER PADDOCK AT 16.00 HRS ON THE NOD TH DAY AT THE WATER POINT (DAM).

     COMMON/CMAIN/NQ,NS,NG,DAY,ID,IDM,IM,ISEAS,IY,UTIME
     COMMON/MVAR/ SHEEP,ALW,AMET,WWOOL,WOOL,CONS(5),TCONS,ACONS(5),
    1 ATCONS,TPF,KRF,ATMEAND,EMET,SSHEEP
     COMMON/CHEAT/ PRESPA(20),HRCAMP(20),TBA(20),WATA(20),RESPA(20),
    1 HUNGA(20),ISTA(20),IPOSA(20),IXPA(20),IYPA(20),TFCA(20),
    2 TSURF,RESP,TBN,SOLAR,DAWN,DUSK,ALEN,RAD
*   RESET VARIABLES.
     W=WWOOL-0.1
     WT=W*SHEEP
     WWOOL=0.1
     WOOL=0.002
     DO10I=1,20
     PRESPA(I)=80.
     HRCAMP(I)=16.
     WATA(I)=3000.
     HUNGA(I)=0.6
     ISTA(I)=3
     IPOSA(I)=26
     IXPA(I)=1
     IYPA(I)=6
     TFCA(I)=0.
  10 CONTINUE
     DO20I=1,5
  20 CONS(I)=0.
     TCONS=0.
*   CALL DAYSIM FOR NOD DAYS (PADDOCK UNGRAZED).
     CALL DAYSIM (NOD,NOP,0,1,0,IO)
     A=SSHEEP-SHEEP
     SHEEP=SSHEEP
     WRITE(IO,2000) W,WT,A
2000 FORMAT (1H0,10(10H**********),/*    SHEARING OCCURS */*    CLIP PE
    1R SHEEP *F5.2* KG --- TOTAL FOR FLOCK *F8.2* KG*/,3X,F3.0* SHEEP D
    2IED SINCE THE PREVIOUS SHEARING.*/)
     RETURN
     END
```

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    DECK LISTING           750313

      SUBROUTINE    SHPHYS
*    SHEEP PHYSIOLOGY CALCULATIONS      CHAPT 9.
*    THE UNITS IN THIS S/R ARE KG AND KCAL (NOT WATTS).
      COMMON/CMAIN/NO,NS,NG,DAY,ID,IDM,IM,ISEAS,IY,UTIME
      COMMON/MVAR/ SHEEP,ALW,AMET,WWOOL,WOOL,CONS(5),TCONS,ACONS(5),
     1 ATCONS,TRF,KRF,ATMEANO,EMET,SSHEEP
      COMMON/CGRAZE/ SALT(5),WATR(5),PREF(5),DIG(5),
     1 PWATI,PSALI,HUNG,CEFO,CONX,CONN,HUNGX,DFC,X1,X2,X3,TFC,H
      DATA WOOLC,ECON/0.030,3600./
*    CALC. METABOLISABLE ENERGY.
      DEI=0.
      TCONS=0.
      DO10I=1,NS
      CONS(I)=CONS(I)/FLOAT(NG)
      ACONS(I)=ACONS(I)+CONS(I)
      DEI=CONS(I)*DIG(I)+DEI
   10 TCONS=TCONS+CONS(I)
*    CALCULATE LIVE WEIGHT AND WOOL GROWTH.
      ATCONS=ATCONS+TCONS
      AMEI=DEI*ECON
      AMERM=134.*ALW**0.75+EMET/(NG*1.163)
      DIGM=DEI/TCONS
      IF(ALW.LT.20.) GO TO 20
      WOOLP=0.0002*ALW
      ECLC=(ALW-20.)*142.3+2720.
      GO TO 30
   20 WOOLP=2.1E-6*AMERM
      ECLC=1523.+113.*EXP(0.118*ALW)
   30 EBAL=AMEI-AMERM-WOOLP*5400.
      EEF=0.8
      IF(EBAL.GE.0.) EEF=0.66*DIGM+0.03
      ALW=ALW+EBAL*EEF/ECLC
      WWOOL=WWOOL+WOOLP
      WOOL=WWOOL*WOOLC
*    CALCULATE MORTALITY.
      AMORT=SHEEP*AMAX1(AMIN1(0.50-0.044*(ALW-25.),0.50),0.06)/365.
      DEATHS=INT(AMORT)
      IF(RANF(0.0).LT.(AMORT-DEATHS)) DEATHS=DEATHS+1.0
      SHEEP=SHEEP-DEATHS
      RETURN
      END
```

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      DECK LISTING           750313

      SUBROUTINE SHPMV
*    SIMULATES ONE DAY OF MOVEMENT AND BEHAVIOUR FOR NG SUBFLOCKS   CHAPT 8.
      COMMON /CCAA/ AGRAZE(24),TGZ,LDAY(20)                                     ZZ*
      COMMON/CMAIN/NQ,NS,NG,DAY,ID,IDM,IM,ISEAS,IY,UTIME
      COMMON/MVAR/ SHEEP,ALW,AMET,WWOOL,WOOL,CONS(5),TCONS,ACONS(5),
     1 ATCONS,TRF,KRF,ATMEAND,EMET,SSHEEP
      COMMON/CPAD/LSHADE(45),LCAMP(45),LWATPT,LA(2,8),LPOS(45),
     1 MXX,MXY,KSPEED
      COMMON/CSHPMV/ RESPMX,RESPH,AMETL,THIRST,DEHYD,TBMX,HCAP,DRINK,CFC
      COMMON/CHEAT/ PRESPA(20),HRCAMP(20),TBA(20),WATA(20),RESPA(20),
     1 HUNGA(20),ISTA(20),IPOSA(20),IXPA(20),IYPA(20),TFCA(20),
     2 TSURF,RESP,TBN,SOLAR,DAWN,DUSK,ALEN,RAD
      COMMON/CGRAZE/ SALT(5),WATR(5),PREF(5),DIG(5),
     1 PWATI,PSALI,HUNG,CEFO,CONX,CONN,HUNGX,DFC,X1,X2,X3,TFC,H
      COMMON/COUT/ ADRINK(24),KDRINK,BEH(37,6),TDRINK,DIST,BOUT(6)
      COMMON/CTEMP/ TMIN,TRANGE,TAIR,TMEAND,CPROB,KLEAR(24),
     1RF,VEL,IWS,IWDIR,EV
      COMMON/CGROW/ EGS(37),EBS(37),TTE(37),TP(37),ON(37),
     1 BIOM(37,5)
      DIMENSION IDT(8,8),WINA(8,3),IGRZ(2,20),DFCA(20),ICONV(45),MIST(8)
      DATA WINA/.2,.325,.435,.545,.655,.765,.875,1.0, .4,.55,.63,.68,.72          *
     1,.77,.85,1.0, .6,.7,.75,.79,.81,.85,.90,1.0/                                 *
      DATA IDT/7,5,7,5,6,1,1,4, 7,2,7,2,6,1,2,2, 7,3,7,3,3,1,1,3,
     17,5,7,5,6,1,4,4, 7,5,7,5,6,1,4,4, 7,5,7,6,6,4,4,4, 7,5,7,4,4,4,4,4
     2, 8,5,8,5,6,1,4,4/
      DATA ICONV/0,0,1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,0,
     1 18,19,20,21,0,22,23,24,25,0,26,27,28,29,0,30,31,32,33,0,34,35,
     2 36,37,0/
      DATA MIST/10HGRAZING   ,10HSHADING   ,10HCAMPING   ,10HRESTING   ,1
     110HTO SHADE  ,10HTO CAMP   ,10HTO WATER  ,10HDRINKING  /
      DATA PP/0.7/
      DATA RESPMN/20./                                                          ZZ*
      DATA AGRAZE/24*0./                                                        ZZ*
      DATA KDAY/1/
      DATA LDAY /10,11,12,120,121,122,123,315,316,317,318, 9*0/

*     NEW DAY                                                                   ZZ*
      IIID=0
      SHG=SHEEP/NG
      CALL HEAT(0,HR)
      HR=INT(DAWN)-2.0
      CALL HEAT(1,HR)
      CALL RESPPT(1)
      EMET=0.
      R=0.58-0.0053*(TMIN+0.2*TRANGE)
      DO10I=1,NS
   10 CONS(I)=0.0

*     CALCULATE THE LOSSES ETC DURING THE NIGHT.
      DO30IG=1,NG
      DFCA(IG)=0.0
      T=24.0-HRCAMP(IG)+HR
      IPOS=IPOSA(IG)
      IJ=ICONV(IPOS)
      BEH(IJ,3)=BEH(IJ,3)+T+1.
      IF(RESP.GE.RESPMN) GO TO 20
      EMET=EMET+(RESPMN-RESP)*R*T
```

```
     CONTINUED

    RESP=RESPMN
 20 WATA(IG)=AMAX1(WATA(IG)-(0.255*(PRESPA(IG)+RESP)+AMETL)*T,0.0)
    HUNGA(IG)=HUNGA(IG)*(H**T)
    HRCAMP(IG)=0.0
 30 CONTINUE

*   HOURLY LOOP
*   WEATHER VARIABLES
 50 HR=HR+UTIME
    IHR=HR+0.5
    ICAMP=0
    CALL TEMPER(HR)
    CALL HEAT(0,HR)
    NGRZ=0
    R=0.58-0.0053*TAIR

*   LOOP FOR SUBFLOCKS.
    DO320IG=1,NG
    INC=0
    IF(HR.GE.DUSK.AND.HRCAMP(IG).NE.0.0) GO TO 320
    CALL RESPPT(IG)
    WAT=WATA(IG)
    HUNG=HUNGA(IG)
    IPOS=IPOSA(IG)
    IST=ISTA(IG)
*   GRAZING
    PWATI=0.0
    PSALI=0.0
    HUNG=HUNG*H
    IF(IST.EQ.1) CALL GRAZE (ICONV(IPOS),IG)
    DFCA(IG)=DFCA(IG)+TFC
*   START SETTING THE FLAGS.
    IFL=6
    IF(HUNG.LT.HUNGX*0.667) GO TO 90
    IFL=7
    IF(HUNG.GT.HUNGX) IFL=8
 90 IF(HR.GE.DUSK) IFL=5
    IF(RESP.GT.RESPMX) GO TO 110
    IF(RESP.GT.RESPH) IFL=4
*   WATER LOSS IN RESPIRATION
100 IF(RESP.GE.RESPMN) GO TO 105
    EMET=EMET+(RESPMN-RESP)*R
    RESP=RESPMN
105 WATL=(0.51*RESP+AMETL)*UTIME
    WAT=AMAX1(WAT+PWATI-WATL-30.0*PSALI,0.0)
    IF(WAT.GT.THIRST) GO TO 200
    II=3
    IF(WAT.LT.DEHYD) II=1
    IFL=MIN0(IFL,II)
    GO TO 200
*   BODY TEMPERATURE RISING.
110 II=4
    TBA(IG)=TBA(IG)+(0.33+0.004*(38.0-TAIR))*(RESP-RESPMX)/(0.83*ALW)
    IF(TBA(IG).GT.TBMX)II=2
    IFL=MIN0(IFL,II)
    RESP=RESPMX
    GO TO 100
200 CONTINUE
```

CONTINUED

```
*   SELECT A NEW STATUS
      IJ=ICONV(IPOS)
      IST=IDT(IFL,IST)
      GO TO (260,280,310,295,210,220,230,250),IST

*   NEW ACTIVITIES.
*   WALKING
  210 IDEST=LSHADE(IPOS)
      GO TO 240
  220 IDEST=LCAMP(IPOS)
      GO TO 240
  230 IDEST=LWATPT
*   CALCULATE THE NEW POSITION
  240 IPOSA(IG)=MOVE(IDEST,IST,IPOS,IXPA(IG),IYPA(IG))
      IF(IPOS.EQ.LPOS(IPOS)) GO TO 245
      IPOS=LPOS(IPOS)
      IYP=(IPOS-1)/MXX
      IXP=IPOS-IYP*MXX
      IYP=IYP+1
      IPOSA(IG)=IPOS
  245 IJ=ICONV(IPOS)
      BEH(IJ,2)=BEH(IJ,2)+1.0
*   SHEEP DRINK IF THEY ARE PASSING A WATER POINT.
      IF(IPOS.NE.LWATPT) GO TO 300
      IF(WAT.GT.0.7*DRINK)  GO TO 300
      BEH(IJ,3)=BEH(IJ,3)-1.0
*   DRINKING
  250 TDRINK=TDRINK+DRINK-WAT
      WAT=DRINK
      KDRINK=KDRINK+1
      ADRINK(IHR)=ADRINK(IHR)+1.0
      BEH(IJ,3)=BEH(IJ,3)+1.0
      GO TO 310
*   GRAZING
  260 NGRZ=NGRZ+1
      IGRZ(1,NGRZ)=IG
      IGRZ(2,NGRZ)=IPOS
      GO TO 300
  280 BEH(IJ,3)=BEH(IJ,3)+1.0
      GO TO 310
  295 BEH(IJ,2)=BEH(IJ,2)+1.0
*   NITROGEN REDISTRIBUTION BY THE SHEEP.
  300 ON(IJ)=ON(IJ)+1.25E-5*SHG
*   FINISH OFF THE SUBFLOCK LOOP
  310 TFCA(IG)=TFC
      WATA(IG)=WAT
      RESPA(IG)=RESP
      HUNGA(IG)=HUNG
*   FORCE SHEEP TO CAMP AT MIDNIGHT.
      IF(HR.GE.24.0) IST=3
      ISTA(IG)=IST
      INC=1
      IF(IST.NE.3) GO TO 320
      PRESPA(IG)=RESP
      HRCAMP(IG)=HR+1.0
      TBA(IG)=TBN
      INC=0
```

```
     CONTINUED

  320 ICAMP=ICAMP+INC
*  END OF SUB-FLOCK HOUR ACTIVITY LOOP..

*   MOVEMENT DURING GRAZING LOOP
      IF(NGRZ.EQ.0) GO TO 460
      AGRAZE(IHR)=AGRAZE(IHR)+NGRZ                                           ZZ*
      TGZ=TGZ+NGRZ                                                           ZZ*
      DO455I=1,NGRZ
      IPOS=IGRZ(2,I)
      IF(IPOS.EQ.0) GO TO 455
      IG=IGRZ(1,I)
      IXP=IXPA(IG)
      IYP=IYPA(IG)
*   DO THE SHEEP MOVE FROM THE CELL.
      P=0.7                                                                    *
      IF(TFCA(IG).GE.CFC) P=0.4                                                *
  400 IF(RANF(0.0).GT.P) GO TO 430
*   CLACULATE THE NEW CELL
      Z=RANF(0.0)
      DO410II=1,8
      IF(Z.LT.WINA(II,IWS)) GO TO 420
  410 CONTINUE
      II=8
  420 IJ=MOD(II+IWDIR-1,8)+1
      IXP=IXP+LA(1,IJ)
      IYP=IYP+LA(2,IJ)
      IF(IXP.LE.0) IXP=1
      IF(IXP.GT.MXX) IXP=MXX
      IF(IYP.LE.0) IYP=1
      IF(IYP.GT.MXY) IYP=MXY
      IPOS=(IYP-1)*MXX+IXP
      IF(IPOS.EQ.LPOS(IPOS)) GO TO 425
*   SHEEP ON THE FENCE.
      IPOS=LPOS(IPOS)
      IYP=(IPOS-1)/MXX
      IXP=IPOS-IYP*MXX
      IYP=IYP+1
*   SPECIAL SECTION FOR WERTIGO. STOPS MOVEMENT TO AND FROM 26 - 31.
  425 CONTINUE
      IF(IPOS.NE.26.AND.IPOS.NE.31) GO TO 427
      IF(IPOSA(IG).NE.26.AND.IPOSA(IG).NE.31) GO TO 427
      IPOS=32
      IXP=2
      IYP=7

  427 IPOSA(IG)=IPOS
      D=SQRT(FLOAT(IABS(IXPA(IG)-IXP)+IABS(IYPA(IG)-IYP)))
      DIST=DIST+D
      IXPA(IG)=IXP
      IYPA(IG)=IYP
  430 IJ=ICONV(IPOS)
      BEH(IJ,1)=BEH(IJ,1)+1.0

*   DO ANY OTHER SHEEP FOLLOW THIS SUBFLOCK.
      I1=I+1
      IF(I1.GT.NGRZ) GO TO 455
      DO450J=I1,NGRZ
      IF(IGRZ(2,J).NE.IPOS) GO TO 450
```

```
       CONTINUED


      IF(RANF(0.0).GT.PP) GO TO 450
      IPOSA(IG)=IPOS
      IXPA(IG)=IXP
      IYPA(IG)=IYP
      IGPZ(2,J)=0
      BEH(IJ,1)=BEH(IJ,1)+1.0
      DIST=DIST+D
  450 CONTINUE
  455 CONTINUE

*   ARE ALL THE SHEEP IN CAMP -- IE END OF THE DAY.
  460 IF(ICAMP.NE.0) GO TO 50
      RETURN
      END
```

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      DECK LISTING             750313

        SUBROUTINE SUMMARY (IO)
*     PRODUCES A PRINTED SUMMARY OF THE SHEEP AND PADDOCK CONDITION.
        COMMON /CCAA/ AGRAZE(24),TGZ,LDAY(20)                                     ZZ*
        COMMON/MVAR/ SHEEP,ALW,AMET,WWOOL,WOOL,CONS(5),TCONS,ACONS(5),
       1 ATCONS,TRF,KRF,ATMEAND,EMET,SSHEEP
        COMMON/CGROW/ EGS(37),EBS(37),TTE(37),TP(37),ON(37),
       1 BIOM(37,5)                                                                *
        COMMON/CWATVB/ SM(3,37),CP(3,37),TC(37),TSM(37),AK(3),Z(10),NZ
        COMMON/CMAIN/NQ,NS,NG,DAY,ID,IDM,IM,ISEAS,IY,UTIME
        COMMON/COUT/ ADRINK(24),KDRINK,BEH(37,6),TDRINK,DIST,BOUT(6)
        COMMON/CSUM/ WHT,Q1,Q4,Q5,Q6,ICC
        COMMON/CTGRZ/TGRZ(37)
        DIMENSION B(6)
        DATA B/6*0./
        DATA KW1,KW2,KW3/10HCONS TODAY,10HCONS MEAN ,10HBIOM TOTAL /
        DATA WHT/6.0/
        DATA PDAY/0./
*     CALCULATE VARIOUS SUMMARY PARAMETERS.
        IES=0
     40 T=DAY-PDAY
        GTM=0.
        DO 50 I=1,37
        GTM=GTM+BEH(I,1)
        BEH(I,6)=BEH(I,6)+BEH(I,1)
        BEH(I,4)=BEH(I,6)+BEH(I,2)
        BEH(I,5)=BEH(I,4)+BEH(I,3)
     50 CONTINUE
        DO60I=1,5
     60 ACONS(I)=ACONS(I)/T
        ATCONS=ATCONS/T
        D=KDRINK
        TG=T*NG
        A=D/TG
        TDRINK=TDRINK/(TG*1000.0)
        DIST=DIST/TG
        GTM=GTM/TG
        DO70I=1,24
        AGRAZE(I)=AGRAZE(I)/TGZ                                                   ZZ*
     70 ADRINK(I)=ADRINK(I)/D
        CRF=TRF-CRF
        KR=KRF-KR
        ATMEAND=ATMEAND/T
*     PRINT SUMMARY.
        WRITE (IO,2000) ICC,IDM,IM,IY,DAY,T,NQ,NS,NG
        WRITE(IO,2001) SHEEP,ALW,WWOOL,WOOL
        WRITE(IO,2006) TRF,KRF,CRF,KR,ATMEAND
        CALL PRINT1 (BIOM,DAY,0,IO)
        WRITE(IO,2003) KW3,BOUT
        WRITE(IO,2002) KW1,CONS,TCONS
        WRITE(IO,2002) KW2,ACONS,ATCONS
        WRITE(IO,2007) GTM,DIST,TDRINK
        WRITE(IO,2004) KDRINK,A,ADRINK
        WRITE(IO,2009) AGRAZE,TGZ                                                 ZZ*
   2009 FORMAT (6(2X,4F5.3),/,2X,F9.0)
        WRITE(IO,2005)
*     PRINT WERTIGO MAPS.
        CALL MAP (BEH(1,1), 0.,-1.,SRGRAZE,1)
```

CONTINUED

```
      CALL MAP (BEH(1,6), 0.,-1.,5RACCUM,1)
      CALL MAP (BEH(1,2), 0.,-1.,9RREST/TRAV,1)
      CALL MAP (BEH(1,3), 0.,-1.,9RSH/CMP/DR,1)
      CALL MAP (BEH(1,4), 0.,-1.,6REXTEN.,1)
      CALL MAP (BEH(1,5), 0.,-1.,5RTOTAL,1)
      CALL MAP (ON,0.,-1.,7RNITRATE,1)
      CALL MAP (SM(1,1),0.,20.,4RSM 1,3)
      CALL MAP (SM(2,1),0.,50.,4RSM 2,3)
      CALL MAP (SM(3,1),0.,50.,4RSM 3,3)
      CALL MAPDMP (0.)
      CALL CENTRE (BEH(1,1),CX,CY,SSS,0)
      WRITE (IO,2008) CX,CY,SSS
      IF(IES.EQ.1) GO TO 200
*   RESET PARAMETERS.
   90 PDAY=DAY
      TGZ=0.                                                           ZZ**
      KDRINK=0
      TDRINK=0.
      DIST=0.
      ATCONS=0.
      CRF=TRF
      KR=KRF
      ATMEAND=0.0
      DO100I=1,37
      BEH(I,1)=0.
  100 CONTINUE
      DO110I=1,24
      AGRAZE(I)=0.                                                      ZZ*
  110 ADRINK(I)=0.
      DO120I=1,5
  120 ACONS(I)=0.
      RETURN

*   SUMMARY AT END OF RUN.
      ENTRY ENDSUM
      IES=1
      IF(DAY.NE.PDAY) GO TO 40
*   EXTRA ENDSUM OUTPUTS...
  200 CONTINUE
      CALL BIOMCH
      BH=0.
      DO210I=1,37
      BEH(I,1)=BIOM(I,1)+BIOM(I,2)+BIOM(I,3)+BIOM(I,4)+BIOM(I,5)
  210 BH=BEH(I,4)+BH
      CALL PRINTAB (BEH,37,6,1,4HF8.0,IO,1)
      T=DAY*NG
      DO220I=1,37
      BEH(I,5)=BEH(I,5)/T
      BEH(I,6)=BEH(I,6)/T
  220 BEH(I,4)=BEH(I,4)/BH
*   CALCOMP PLOTTING.
      CALL WERTMP (BEH(1,5),37,WHT,Q5,0.,0.,4,11HTOTAL TIME ,5HHOURS)
      CALL WERTMP (BEH(1,4),37,WHT,Q4,0.,0.,4,14HEXTENSIVE TIME,5HPROPN)
      CALL WERTMP (BEH(1,6),37,WHT,Q6,0.,0.,4,12HGRAZING TIME,5HHOURS)
      Q=0.
      CALL WERTMP (TGRZ,37,WHT,Q,0.,0.,4,17HTOTAL CONSUMPTION,5HKG/HA)
      CALL WERTMP (BEH(1,1),37,WHT,Q1,0.,0.,4,13HTOTAL BIOMASS,5HKG/HA)
      GO TO 90
```

```
      CONTINUED


2000 FORMAT (A1,/,12(10H::::::::::),/,*0  SUMMARY FOR *3(I2*-*),1X,F6.0
    1* DAYS OF RUN *F4.0* DAYS SINCE THE LAST SUMMARY*,/,
    2 80X,*CELLS *I3*    SPECIES *I3*    GROUPS *I3)
2001 FORMAT (*   SHEEP NUMBERS *F6.0*     BODY WEIGHT *F5.1* KG     WOO
    1L WEIGHT *F5.2* KG     WOOL LENGTH *3PF4.0* MM*)
2002 FORMAT (3X,A10,1X,F6.3,4(20X,F6.3),* TOT *F6.3)
2003 FORMAT (3X,A10,1X,F6.1* TONNES*13X,F6.1,3(20X,F6.1),* TOT *F6.1)
2004 FORMAT (*   SHEEP DRANK *I4* TIMES IE *F4.2* TIMES EACH, PER DAY
    1 .... HOURLY DISTRIBUTION:*/,6(2X,4F5.3))
2005 FORMAT (/*   ACTIVITIES ETC*)
2006 FORMAT (*   TOTAL RF *F6.1* MM   NO. OF WET DAYS *I4* .... OR *F6.1
    11* MM AND *I4* DAYS SINCE THE LAST SUMMARY.    MEAN DAY TEMP. *F6.1
    21* C*)
2007 FORMAT (*0  GRAZING TIME *F5.2* HOURS     WALKING *F5.2* KM     DR
    1INKING *F5.2* LITRES PER SHEEP PER DAY *)
2008 FORMAT (*   CENTRE POINT OF GRAZING ACTIVITIES *2F5.2* DISPERSAL *F7.3)
    1 F7.3)
     END
```

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      SUBROUTINE TEMPER (HR)
*   CALCULATES AIR TEMPERATURE AND CLOUD COVER.
      COMMON/CMAIN/NQ,NS,NG,DAY,ID,IDM,IM,ISEAS,IY,UTIME
      COMMON/CTEMP/ TMIN,TRANGE,TAIR,TMEAND,CPROB,KLEAR(24),
     1RF,VEL,IWS,IWDIR,EV
      COMMON/CRAND/ ZZR,ZZT,ZZW,ZZZ
      DIMENSION TM(12),TR(12),TAB(12),PH(24),CLPROB(12),ACLEAR(12)
      DATA TR/2*15.,13.,7*10.,12.,14./
      DATA  TM/3*8.,7.,5.,1.,1.,2.,5.,3*8./
      DATA P,PMX,AK1,AK2/0.03,0.8,6.0,0.4/
      DATA TPROB,PDAY/0.,0./
      DATA TAB /50.,50.,45.,40.,35.,30.,30.,35.,40.,45.,50.,50./
      DATA PH/ .20,.15,.11,.07,.03,.00,.03,.12,.25,.41,.59,.75,.88,.97,
     1 1.0,.97,.88,.75,.59,.41,.37,.32,.28,.23/
      DATA CLPROB/3*.5,4*.3,3*.4,2*.5/
      DATA ACLEAR/27.,27.,26.,22.,22.,19.,18.,19.,19.,23.,26.,27./

      IF(DAY.EQ.PDAY) GO TO 20
      CALL RANGET (ZZZ)
      CALL RANSET (ZZT)
      PDAY=DAY
*   HAS A COOL CHANGE OCCURRED.
      TPROB=TPROB+P
      IF(TPROB.GT.PMX) TPROB=PMX
      IF(RANF(0.0).GT.TPROB) GO TO 10
*   NEW CYCLE
      TPROB=0.0
      TMIN=TM(IM)
      TRANGE=TR(IM)
*   CALCULATE THE TEMPERATURE.
   10 TMIN=TMIN+AK1*(RANF(0.0)-AK2)
      TRANGE=TRANGE+AK1*(RANF(0.0)-AK2)
      TX=TMIN+TRANGE
      CPROB=CLPROB(IM)
      IF(TX.LT.ACLEAR(IM)) GO TO 14
*   CALCULATE THE CLEAR HOURS.
      DO12I=1,24
   12 KLEAR(I)=1
      CPROB=1.0
      GO TO 18
   14 DO16I=1,24
      KLEAR(I)=1
      IF(RANF(0.0).GT.CPROB) KLEAR(I)=0
   16 CONTINUE
*   CHECK THAT THE TEMPERATURE IS WITHIN THE LIMITS.
   18 IF(TX.LT.TAB(IM)) GO TO 19
      TX=(TX-TAB(IM))/2.0
      TMIN=TMIN-TX
      TRANGE=TRANGE-TX
   19 TMEAND=TMIN+0.72*TRANGE
      CALL RANGET (ZZT)
      CALL RANSET(ZZZ)
*   SAME DAY
   20 IHR=HR+0.5
      TAIR=TMIN+PH(IHR)*TRANGE
      RETURN
      END
```

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      SUBROUTINE WATVB (RF,EV)
*    SOIL MOISTURE MODEL
*    OPERATES FOR NQ CELLS AND NZ ZONES .  EACH CELL MAY HAVE DIFFERENT
*    CP VALUES, BUT THE AK AND Z VALUES ARE CONSTANT.
      COMMON/CMAIN/NQ,NS,NG,DAY,ID,IDM,IM,ISEAS,IY,UTIME
      COMMON/CWATVB/ SM(3,37),CP(3,37),TC(37),TSM(37),AK(3),Z(10),NZ
      DIMENSION RO(38),IRO(37),IORD(37)

      DATA IRO/38,38,38,38, 1, 2, 2,38,38, 6, 7, 7,38,38,10,11,21,
     138,19,24,38,22,27,27,38,22,27,32,38,27,31,32,38,34,35,36,38/
      DATA IORD/37,36,35,34,33,31,30,29,28,26,25,23,20,19,18,17,16,
     115,14,13,12, 9, 8, 5, 4, 3,32,27,24,22,21,11,10, 7, 6, 2, 1/
      DATA RO/38*0./

*    WAS RAIN RECORDED
      IF(RF.LE.0) GO TO 50
      RO(38)=0.0
*    CALC RUNOFF
      DO40N=1,NQ
      NK=IORD(N)
      NL=IRO(NK)
      RFK=RF+RO(NK)
      RO(NK)=0.0
      IF(NL.EQ.NK) GO TO 10
      SSM=TC(NK)-TSM(NK)
      R=(AMAX1((RFK-0.2*SSM),0.0)**2)/(RFK+0.8*SSM)
      RO(NL)=RO(NL)+R
      RFK=RFK-R
*    CALC SM INCREMENT
   10 DO 20I=1,NZ
      A=CP(I,NK)-SM(I,NK)
      RFK=RFK-A
      IF(RFK.LE.0.) GO TO 30
   20 SM(I,NK)=CP(I,NK)
      GO TO 40
   30 SM(I,NK)=SM(I,NK)+RFK+A
   40 CONTINUE

*    CALC EVAPORATIVE LOSSES
   50 DO 60N=1,NQ
      TSM(N)=0.
      DO60I=1,NZ
      A=10.0*SM(I,N)/(CP(I,N)+0.0001)
      IA=INT(A+1.0)
      B=Z(IA)*AK(I)*EV
      SM(I,N)=AMAX1(SM(I,N)-B,0.0)
   60 TSM(N)=TSM(N)+SM(I,N)
      RETURN
      END
```

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    DECK LISTING            750313

      SUBROUTINE WERTMP (QA,N,HT,Q,XP,YP,IOPT,IHEAD,IU)

*     PLOTS MAPS OF WERTIGO PADDOCK.
*     THE COORD OF X AND Y RELATIVE TO THE PRESENT ORIGIN ARE STORED IN QX AND QY.
*     HEADINGS AND SCALES, AND THE QUADRAT POSITIONS ARE OPTIONAL.
*
*     N --- SET TO 45 OR 37 DEPENDING ON THE FORMAT OF THE ARRAY.
*     Q --- THE VALUE REPRESENTED BY THE LARGEST SYMBOL. IF Q=0. IT IS SET AUTOM.
*     HT --- HEIGHT OF MAP IN INCHES (RATIO OF HEIGHT TO WIDTH = 10:6)
*     XP AND YP --- THE POSITION OF THE MAP RELATIVE TO THE PRESENT ORIGIN,
*       THE MAP WILL BE PLOTTED FROM XP TO XP+0.6*HT, AND YP TO YP-HT.
*       IFYP=0.0 THEN THE POSITIONING IS DONE AUTOMATICALLY.
*     IOPT --- IF NEGATIVE, THEN NO SCALE OR HEADING PLOTTED,
*       IABS(IOPT)=0   NO QUADS POSITIONS CALCULATED OR PLOTTED,
*       IABS(IOPT)=1   CALCS POSITION BUT NO PLOTTING
*       IABS(IOPT)=2   POSITIONS CALCULATED AND PLOTTED, ALL THE SAME SIZE. QA(1)
*       IABS(IOPT)=3   POSITIONS CALCULATED AND PLOTTED, SIZES AS IN QS.
*       IABS(IOPT)=4   POSITIONS CALCULATED AND PLOTTED, SIZES AUTOMATICALLY
*                      SCALED SO THAT THE AREA IS PROPORTIONAL TO THE VALUE IN QS.
*       IABS(IOPT)=7,8,9   POSITIONS OF QUADRATS ASSUMED TO ALREADY BE IN QS
*                          7,8, AND 9 ARE OTHERWISE EQUIVALENT TO 2,3, AND 4.
*     IHEAD --- A 20 CHAR. HEADING.
*     IU --- A 10 CHAR. DESCRIPTION OF THE UNITS.  IT ALSO PRINTS THE SCALE.
*       IU IS ONLY PLOTTED IF THE HEADINGS ARE REQUESTED AND EVEN THEN
*       IU CAN BE SUPRESSED BY SETTING IU=0

      COMMON/CWTMP/QX(45),QY(45),YB,XE,HTX,IO,KN,TOP
      DIMENSION QA(N),IHEAD(2),QS(45),ITA(37)
      DATA ITA/3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,21,22,23,24,
     1 26,27,28,29,31,32,33,34,36,37,38,39,41,42,43,44/
      DATA IST,HTX,XE,TOP/1,0.,0.,10./
      DATA IO,KN/2,1/
      IOP=IABS(IOPT)
      IF(IOP.LT.7) GO TO 4
      IOP=IOP-5
      GO TO 15
    4 IF(YP.NE.0.0) GO TO 60
*     WILL IT FIT
      IF(IST.NE.1.AND.YB.GE.HT) GO TO 5
      XE=XE+HTX*0.6
      HTX=0.0
      YB=TOP
    5 IF(HT.GT.HTX) HTX=HT

*     PLOT THE OUTLINE
      S=HT/10.0
      SS=0.5*S
      X=YB-2.3*S
      CALL PLOT(XE,X,3)
      Y=YB-9.8*S
      CALL PLOT (XE,Y,2)
      CALL PLOT (XE+3.65*S,Y,2)
      CALL PLOT (XE+5.1*S,YB-0.6,2)
      CALL PLOT  (XE,X,2)
      IF(IOP.LT.1) GO TO 40

*     CALC QUADRAT POSITIONS.
```

0037720

CONTINUED

```
       Y=YB-1.3*SS
       K=0
       DO10I=1,9
       X=XE-SS
       Y=Y-S
       DO10J=1,5
       K=K+1
       X=X+S
       QX(K)=X
    10 QY(K)=Y
       IF(IOP.LT.2) GO TO 40

*     NOW PLOT THEM
    15 IF(IOP.GT.2) GO TO 8
*     CONSTANT.POINT SIZE.
       Q=QA(1)*QA(1)
       DO14I=1,45
    14 QS(I)=Q
       X=1.0
       Q=1.0
       GO TO 19
     8 X=AMAX1(S,0.1)
       DO9I=1,45
     9 QS(I)=0.
       IF(N.EQ.37) GO TO 12
       DO11I=1,45
    11 QS(I)=QA(I)
       GO TO 18
    12 DO13I=1,37
       K=ITA(I)
    13 QS(K)=QA(I)
    18 IF(Q.NE.0..AND.IOP.EQ.4) GO TO 19
       Q=1.0
    16 IF(IOP.EQ.3) GO TO 19
*     AUTO SCALING
       Q=QS(1)
       DO17I=2,45
    17 IF(QS(I).GT.Q) Q=QS(I)
       IF(Q.EQ.0.0) GO TO 70
*     PLOT SYMBOLS
       QL=10.0**INT(ALOG10(Q))
       IF(QL.LT.1.0) QL=QL/10.0
       Q=(INT(Q/QL+0.9999))*QL
    19 DO20I=3,19
       SQ=SQRT(QS(I)/Q)*X
       CALL SYMBOL (QX(I),QY(I),SQ,KN,0.0,-1)
    20 CONTINUE
       DO30I=21,44
       IF((I/5)*5.EQ.I) GO TO 30
       SQ=SQRT(QS(I)/Q)*X
       CALL SYMBOL (QX(I),QY(I),SQ,KN,0.0,-1)
    30 CONTINUE
    40 IF(IOPT.LT.0) GO TO 50

*     PLOT SCALE AND HEADING
       XL=AMAX1(0.2*S,0.1)
       IF(IOP.LE.3) GO TO 45
```

CONTINUED

```
      WRITE(IO,2000) Q,X
 2000 FORMAT (1H0,10X,*CALL TO WERTMP EXECUTED::::*,/10X*THE HIGHEST VALUE
     1UE *G12.5*  IS REPRESENTED BY A SYMBOL *F5.2* INCHES HIGH*)
      IF(N.EQ.37.AND.IOP.GT.3)  CALL CENTRE (QA,CX,CY,SSS,IO)
      CALL SYMBOL (XE+4.5*5,YB-7.4*5,.32*X,KN,0.0,-1)
      CALL SYMBOL (XE+4.5*S,YB-8.2*S,.71*X,KN,0.0,-1)
      CALL SYMBOL (XE+4.5*S,YB-9.3*S,X,KN,0.0,-1)
      IF(IU.EQ.0) GO TO 45
*    PLOT UNITS
      X=XE+SS
      Y=YB-HT-0.2
      CALL SYMHOL (X,Y,XL,5HUNITS  ,0.0,5)
      CALL SYMBOL (X+6.*XL,Y,XL,IU,0.0,10)
      CALL NUMBER (XE+3.8*S,Y,XL,Q,0.0,4HG7.1)

*    PLOT HEADINGS
   45 CALL SYMBOL (XE+SS,YB-SS,XL,IHEAD,0.0,20)
      CALL PLOT(XE+S,YB-S,3)
      CALL PLOT(XE+3.*S,YB-S,2)
      CALL SYMBOL (XE+1.8*S,YB-0.9*S,XL,4HMILE,0.0,4)
      CALL PLOT (XE+S,YB-1.1*S,3)
      CALL PLOT(XE+2.27*S,YB-1.1*S,2)
      CALL SYMBOL (XE+1.5*S,YB-1.2*S-XL,XL,2HKM,0.0,2)
      GO TO 50

*    POSITION THE GRAPH ON THE PAGE.
   60 YB=YP
      XE=XP
      HTX=0.0
      GO TO 5
   70 WRITE(2,2001) Q,QS
 2001 FORMAT (*   WERTMP:::: REQUEST TO PLOT A ZERO MATRIX IGNORED,  Q= *
     1 *G12.5,/,(5G12.5))
   50 YB=YB-HT
      IF(IU.NE.0) YB=YB-0.5
      IST=0
      RETURN
      END
```

DECK LISTING 750313

```
      SUBROUTINE WIND (ISEAS)
*    MODELS WIND FOR OODNADATTA
*    DOES NOT CONSIDER PERSISTENCE NOR CORRELATION WITH OTHER CLIMATIC VARIABLES
*       OUTPUT::: IWS == WIND STENGTH    1=CALM , 2= <9KT , 3= >9KT
*                 IWDIR == WIND DIRECTION    NW=1 , N=2 , ....  W=8.
      COMMON/CTEMP/ TMIN,TRANGE,TAIR,TMEAND,CPROB,KLEAR(24),
     1RF,VEL,IWS,IWDIR,EV
      COMMON/CRAND/ ZZR,ZZT,ZZW,ZZZ
      DIMENSION WLIST(17,4)
      DATA JWDIR/1/
      DATA WLIST/.24,.26,.28,.30,.36,.44,.57,.59,.60,.62,.66,.71,.79,.88
     1,.97,.99,1.0,.31,.33,.35,.36,.40,.47,.54,.56,.58,.59,.63,.70,.79,.
     289,.97,.99,1.0,.33,.35,.39,.42,.44,.47,.52,.57,.59,.64,.70,.75,.81
     3,.87,.94,.97,1.0,.22,.24,.31,.36,.40,.45,.59,.64,.66,.69,.72,.78,.
     485,.90,.98,.99,1.0/
      DATA WCON/5.36/

      CALL RANGET (ZZZ)
      CALL RANSET (ZZW)
      Z=RANF(0.0)
      DO10I=1,17
      IF(Z.LE.WLIST(I,ISEAS)) GO TO 20
   10 CONTINUE
   20 IF(I.GT.9) GO TO 40
      IF(I.GT.1) GO TO 30
*    CALM
      VEL=0.5
      IWS=1
      IWDIR=JWDIR
      GO TO 50
*     < 9 KT WIND.
   30 IWS=2
      VEL=RANF(0.0)*WCON
      IWDIR=I-1
      GO TO 50
*     > 9 KT WIND.
   40 IWS=3
      VEL=(1.0+RANF(0.0))*WCON
      IWDIR=I-1
   50 CALL RANGET (ZZW)
      CALL RANSET(ZZZ)
      RETURN
      END
```

APPENDIX 6

An example of the summary output from the first year of run R-2.

Most of the output is self explanatory, but a few extra details should be described. The species biomasses are printed as (disorted) maps of Wertigo paddock. The biomasses are given as kg ha^{-1}, but the total biomasses are printed below them as tonnes in the whole paddock. The consumptions are given as kg hd^{-1} day^{-1}. The 'HOURLY DISTRIBUTION' data lists the drinking distribution (first line) and the grazing time distribution (second line) in the intervals 0.00 - 1.00 hr to 23.00 - 24.00 hr. The values printed are the proportion of the total number of drinks by all sheep over the whole time period, and the proportion of the total number of hours spent grazing.

The activities are shown as (disorted) maps of Wertigo. The values (v) are scaled and the origin (g) and units (u) are shown below each map. A printed value v represents a true value within the interval

$$g + (u - 1.5) * v \quad \text{to} \quad g + (u + 1.5) * v.$$

The maps represent:

GRAZE	...	the total grazing time in each cell since the last summary (hr)
ACCUM	...	the accumulated grazing time (hr)
REST/TRAV	...	the accumulated travelling and resting time in each cell (hr)
SH/CMP/DR	...	the accumulated shading, camping and drinking time in each cell (hr)
EXTEN	...	the accumulated 'extensive' time in each cell (hr)
TOTAL	...	the accumulated time of all activities in each cell (hr)

NITRATE	...	soil nitrate (kg ha^{-1})
SM1, SM2 & SM3	...	the soil moisture values on the day of the summary (mm)

```
::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

SUMMARY FOR  1- 3- 1-     60. DAYS OF RUN  60. DAYS SINCE THE LAST SUMMARY
                                                                              CELLS  37     SPECIES   5    GROUPS  10
SHEEP NUMBERS   360.      BODY WEIGHT  40.0 KG     WOOL WEIGHT   .10 KG     WOOL LENGTH    5. MM
TOTAL RF    0.0 MM    NO. OF WET DAYS   0 .... OR    0.0 MM AND    0 DAYS SINCE THE LAST SUMMARY.     MEAN DAY TEMP.     0.0 C

         GRASS                      BASSIA                STANDING DEAD           ATRIPLEX VESICARIA          KOCHIA SEDIFOLIA   60.

            50.  50.  50.             50.  50.  50.            100. 100. 100.            170.  20. 110.            130. 200. 410.
  50.  50.  50.  50.  50.   50.  50.  50.  50.  50.  100. 100. 100. 100. 100.  190. 150.  30.  80.  20.  150. 260. 140. 190. 320.
  50.  50.  50.  50.  50.   50.  50.  50.  50.  50.  100. 100. 100. 100. 100.  290. 100. 280.  20.  20.  170. 360. 120. 270. 400.
  50.  50.  50.  50.        50.  50.  50.  50.       100. 100. 100. 100.       160. 230. 130. 200.       250. 420. 280. 120.
  50.  50.  50.  50.        50.  50.  50.  50.       100. 100. 100. 100.        90. 180. 190. 110.       290. 110. 260. 280.
  50.  50.  50.  50.        50.  50.  50.  50.       100. 100. 100. 100.         0. 110. 180. 180.       600. 150. 220.  90.
  50.  50.  50.  50.        50.  50.  50.  50.       100. 100. 100. 100.       300. 220. 290. 210.       110. 110.  60. 100.
  50.  50.  50.  50.        50.  50.  50.  50.       100. 100. 100. 100.       430. 170.  50. 120.       290. 210. 230. 180.
  50.  50.  50.  50.        50.  50.  50.  50.       100. 100. 100. 100.       320. 180.  80. 280.       190. 210.  30.   0.
BIOM TOTAL    0.0 TONNES                  0.0                       0.0                       0.0                       0.0 TOT    0.0
CONS TODAY  0.000                        0.000                     0.000                     0.000                     0.000 TOT  0.000
CONS MEAN   0.000                        0.000                     0.000                     0.000                     0.000 TOT  0.000

GRAZING TIME  0.00 HOURS      WALKING  0.00 KM      DRINKING  0.00 LITRES PER SHEEP PER DAY
SHEEP DRANK     0 TIMES IF 0.00 TIMES EACH, PER DAY    .... HOURLY DISTRIBUTION:
   I    I    I    I      I    I    I    I      I    I    I    I      I    I    I    I      I    I    I    I      I    I    I    I
   I    I    I    I      I    I    I    I      I    I    I    I      I    I    I    I      I    I    I    I      I    I    I    I
       0.

ACTIVITIES ETC
       GRAZE     ACCUM REST/TRAV SH/CMP/DR    EXTEN.     TOTAL   NITRATE     SM 1      SM 2      SM 3
                                                                      999       444       444       444
                                                                    99999     44444     44444     44444
                                                                    99999     44444     44444     44444
                                                                     9999      4444      4444      4444
                                                                     9999      4444      4444      4444
                                                                     9999      4444      4444      4444
                                                                     9999      4444      4444      4444
                                                                     9999      4444      4444      4444
                                                                     9999      4444      4444      4444
ORIG  0.        0.         0.        0.        0.        0.        0.        0.         0.        0.
UNITS 0.        0.         0.        0.        0.        0.        .100E+00  2.00       5.00      5.00
TOTAL 0.        0.         0.        0.        0.        0.        37.0      370.       925.      925.
 CENTRE POINT OF GRAZING ACTIVITIES  0.00 0.00 DISPERSAL    0.000
```

```
::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 SUMMARY FOR  6- 3- 1-    65. DAYS OF RUN   5. DAYS SINCE THE LAST SUMMARY
                                                                         CELLS  37     SPECIES   5     GROUPS  10
 SHEEP NUMBERS   300.     BODY WEIGHT  40.0 KG      WOOL WEIGHT    .10 KG      WOOL LENGTH    2. MM
 TOTAL RF     0.0 MM    NO. OF WET DAYS     0 .... OR     0.0 MM AND     0 DAYS SINCE THE LAST SUMMARY.     MEAN DAY TEMP.    19.9 C

          GRASS                            BASSIA                      STANDING DEAD               ATRIPLEX VESICARIA          KOCHIA SEDIFOLIA   65.

            44.  44.  44.                45.  45.  45.                105. 105. 105.               168.  20. 108.   ..            129. 198. 406.
 44.  44.  44.  44.  44.   45.  45.  45.  45.  45.   105. 105. 105. 105. 105.   187. 148.  30.  79.  20.   149. 257. 139. 188. 317.
 44.  44.  44.  44.  44.   45.  45.  45.  45.  45.   105. 105. 105. 105. 105.   286.  99. 276.  20.  20.   168. 356. 119. 267. 396.
 44.  44.  44.  44.        45.  45.  45.  45.        105. 105. 105. 105.        158. 227. 128. 197.        248. 416. 277. 119.
 44.  44.  44.  44.        45.  45.  45.  45.        105. 105. 105. 105.         89. 178. 187. 108.        287. 109. 257. 277.
 44.  44.  44.  44.        45.  45.  45.  45.        105. 105. 105. 105.          0. 108. 178. 178.        594. 149. 218.  89.
 44.  44.  44.  44.        45.  45.  45.  45.        105. 105. 105. 105.        296. 217. 286. 207.        109. 109.  59.  99.
 44.  44.  44.  44.        45.  45.  45.  45.        105. 105. 105. 105.        424. 168.  49. 118.        287. 208. 228. 178.
 44.  44.  44.  44.        45.  45.  45.  45.        105. 105. 105. 105.        316. 178.  79. 276.        188. 208.  30.   0.
 BIOM TOTAL  103.6 TONNES                105.9                      248.2                       371.7                       501.2 TOT 1330.7
 CONS TODAY  0.000                       0.000                      0.000                       0.000                       0.000 TOT  0.000
 CONS MEAN   0.000                       0.000                      0.000                       0.000                       0.000 TOT  0.000

 GRAZING TIME  0.00 HOURS     WALKING  0.00 KM     DRINKING  0.00 LITRES PER SHEEP PER DAY
 SHEEP DRANK     0 TIMES IE 0.00 TIMES EACH, PER DAY    .... HOURLY DISTRIBUTION:
     I    I    I    I      I    I    I    I      I    I    I    I      I    I    I    I      I    I    I    I      I    I    I    I
     I    I    I    I      I    I    I    I      I    I    I    I      I    I    I    I      I    I    I    I      I    I    I    I
        0.

 ACTIVITIES ETC
          GRAZE      ACCUM REST/TRAV SH/CMP/DR     EXTEN.       TOTAL   NITRATE       SM 1       SM 2       SM 3
                                                                            999        444        444        444
                                                                          99999      44444      44444      44444
                                                                          99999      44444      44444      44444
                                                                           9999       4444       4444       4444
                                                                           9999       4444       4444       4444
                                                                           9999       4444       4444       4444
                                                                           9999       4444       4444       4444
                                                                           9999       4444       4444       4444
                                                                           9999       4444       4444       4444
 ORIG   0.          0.          0.          0.          0.          0.        0.         0.         0.         0.
 UNITS  0.          0.          0.          0.          0.          0.        .100E+00   2.00       5.00       5.00
 TOTAL  925.        925.        925.        925.        925.        925.      37.0       342.       917.       921.
  CENTRE POINT OF GRAZING ACTIVITIES  0.00 0.00 DISPERSAL   0.000
  MEAN TIME PER DAY OF SIMULATION   .027 SECS.

***************************************************************************************************************************

   SHEARING OCCURS
   CLIP PER SHEEP  0.00 KG --- TOTAL FOR FLOCK      0.00 KG
   0. SHEEP DIED SINCE THE PREVIOUS SHEARING.
```

```
::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

  SUMMARY FOR  4- 6- 1-   155. DAYS OF RUN  90. DAYS SINCE THE LAST SUMMARY
                                                                           CELLS  37    SPECIES   5    GROUPS  10
  SHEEP NUMBERS   295.       BODY WEIGHT  40.8 KG      WOOL WEIGHT    .82 KG     WOOL LENGTH  25. MM
  TOTAL RF    64.8 MM   NO. OF WET DAYS     7 .... OR    64.8 MM AND     7 DAYS SINCE THE LAST SUMMARY.    MEAN DAY TEMP.    19.7 C

             GRASS                           BASSIA                      STANDING DEAD              ATRIPLEX VESICARIA            KOCHIA SEDIFOLIA  155.

             195. 190. 168.                144. 141. 132.                   73.  73.  73.                 171.  20. 107.              128. 198. 395.
 192. 180. 201. 191. 176.  142. 137. 146. 141. 135.   73.  73.  73.  73.  73.  189. 148.  31.  80.  20.  147. 253. 140. 188. 312.
 187. 171. 194. 181. 169.  140. 133. 143. 133. 133.   73.  73.  73.  73.  73.  285.  98. 278.  20.  20.  166. 348. 118. 265. 387.
 179. 168. 177. 195.       138. 133. 136. 144.        72.  72.  73.  73.       156. 220. 127. 198.       243. 402. 272. 118.
 166. 192. 177. 175.       136. 145. 137. 136.        70.  71.  72.  72.        83. 174. 184. 107.       282. 109. 252. 273.
 130. 189. 180. 200.       127. 145. 140. 147.        64.  71.  71.  72.         0. 105. 172. 178.       570. 149. 215.  89.
 194. 177. 201. 197.       144. 146. 147. 145.        72.  67.  72.  72.       295. 197. 286. 207.       108. 109.  59.  99.
 179. 182. 181. 188.       138. 139. 139. 142.        72.  72.  72.  72.       410. 166.  49. 118.       277. 205. 226. 177.
 184. 184. 223. 216.       139. 139. 155. 154.        73.  73.  72.  72.       313. 177.  82. 278.       184. 205.  30.   0.
  BIOM TOTAL   437.3 TONNES                332.8                    170.6                     367.6                     492.8 TOT 1801.1
  CONS TODAY    .583                        .200                     .041                      .128                      .038 TOT    .989
  CONS MEAN     .388                        .142                     .125                      .318                      .065 TOT  1.037

  GRAZING TIME   8.75 HOURS      WALKING  8.67 KM      DRINKING  2.60 LITRES PER SHEEP PER DAY
  SHEEP DRANK   788 TIMES IE  .88 TIMES EACH, PER DAY   .... HOURLY DISTRIBUTION:
 0.0000.0000.0000.000    .088 .142 .089 .036   .036 .052 .051 .030   .047 .065 .039 .039   .033 .136 .095 .023  0.0000.0000.0000.000
 0.0000.0000.0000.000    .059 .093 .103 .108   .109 .088 .075 .074   .060 .048 .042 .049   .065 .0260.0000.000  0.0000.0000.0000.000
     7871.

  ACTIVITIES ETC
              GRAZE        ACCUM REST/TRAV SH/CMP/DR     EXTEN.       TOTAL    NITRATE      SM 1        SM 2        SM 3
               ...          ...         ...        ...         ...         ...          877        666         666         444
              0....        0....       0....      0..0.       0....       0..0.       87877      66666       66666       44444
              0....        0....       .....      .....       .....       .....       77877      66666       66666       44444
              0000         0000        .0..       ....        00.0        ....        7778       6666        6666        4444
              2200         2200        0.0.       ....        1100        00..        7877       6666        6666        4444
              7221         7221        7110       8.3.        8210        802.        7878       6666        6666        4444
              0711         0711        00.0       ....        0300        .1..        8888       6666        6666        4444
              0000         0000        0...       1...        0000        1...        7777       6666        6666        4444
              0001         0001        ...0       ...1        0001        ...1        7788       6666        6666        4444
 ORIG      0.           0.          0.          0.          0.          0.          0.          0.          0.          0.
 UNITS    150.         150.        150.        500.        300.        800.      .100E+00     2.00        5.00        5.00
 TOTAL   .787E+04    .787E+04    .407E+04    .969E+04    .119E+05    .216E+05     30.8       488.       .130E+04     860.
  CENTRE POINT OF GRAZING ACTIVITIES   2.24 3.85 DISPERSAL    3.956
```

```
::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
 SUMMARY FOR  2- 9- 1-   245. DAYS OF RUN  90. DAYS SINCE THE LAST SUMMARY
                                                                 CELLS  37     SPECIES   5    GROUPS  10
 SHEEP NUMBERS   288.       BODY WEIGHT  42.7 KG      WOOL WEIGHT  1.57 KG     WOOL LENGTH  47. MM
 TOTAL RF    85.6 MM    NO. OF WET DAYS    16 .... OR    20.7 MM AND     9 DAYS SINCE THE LAST SUMMARY.    MEAN DAY TEMP.    13.3 C

               GRASS                             BASSIA                       STANDING DEAD              ATRIPLEX VESICARIA            KOCHIA SEDIFOLIA  245.

               289. 273. 232.                   188. 182. 166.                         45.  45.  44.                183.  22. 112.                    137. 213. 412.
 281. 256. 296. 274. 245.  186. 176. 191. 183. 171.   44.  45.  45.  45.  44.  201. 156.  33.  86.  21.  157. 267. 151. 201. 329.
 272. 237. 245. 256. 233.  183. 167. 187. 176. 166.   44.  44.  44.  44.  45.  302. 102. 296.  21.  21.  175. 366. 125. 281. 406.
 252. 232. 249. 287.       176. 167. 174. 190.        44.  44.  44.  44.       164. 228. 134. 211.       257. 418. 287. 127.
 224. 278. 249. 244.       172. 191. 175. 173.        42.  43.  44.  44.        86. 184. 193. 112.       298. 117. 266. 288.
 152. 276. 252. 297.       152. 189. 180. 196.        38.  43.  43.  44.         0. 111. 179. 190.       594. 159. 228.  96.
 284. 242. 290. 291.       184. 190. 196. 193.        44.  40.  44.  44.       312. 202. 305. 221.       115. 118.  63. 106.
 251. 258. 254. 269.       177. 179. 178. 184.        44.  44.  44.  44.       423. 175.  52. 125.       289. 218. 242. 189.
 263. 250. 343. 330.       180. 179. 211. 209.        44.  44.  44.  44.       328. 186.  89. 298.       195. 218.  33.   0.
  BIOM TOTAL  625.1 TONNES              430.2                        103.6                    388.0                       521.2 TOT 2068.1
  CONS TODAY   .660                     .198                         .018                     .145                        .018 TOT  1.038
  CONS MEAN    .607                     .196                         .028                     .148                        .026 TOT  1.005

  GRAZING TIME  7.62 HOURS     WALKING  7.06 KM     DRINKING  2.10 LITRES PER SHEEP PER DAY
  SHEEP DRANK  585 TIMES IF  .65 TIMES EACH, PER DAY    .... HOURLY DISTRIBUTION:
 0.0000.0000.0000.000    .074 .277 .178 .007   .007 .009 .015 .012   .017 .024 .031 .058   .050 .227 .0150.000  0.0000.0000.0000.000
 0.0000.0000.0000.000    .025 .092 .116 .130   .131 .126 .115 .096   .054 .031 .018 .018   .0480.0000.0000.000  0.0000.0000.0000.000
      6961.

  ACTIVITIES ETC
           GRAZE       ACCUM  REST/TRAV  SH/CMP/UR      EXTEN.       TOTAL    NITRATE       SM 1        SM 2       SM 3
             ..0         ...        ...        ...         ...         ...        888        444         555        333
           0..00       .....      .....      0..1.       0....       0..0.      88888      44444       55555      33333
           ..0..       .....      .....      .....       .....       .....      88888      44444       55555      33333
           1000        0000       00..       ....        0000        ....       8888       4444        5555       3333
           3211        2100       0000       ....        1100        00..       8888       4444        5555       3333
           8321        6210       7010       9.4.        8220        703.       9888       4444        5555       3333
           1811        6600       00.0       ....        0400        .1..       8988       4444        5555       3333
           2111        1000       1..0       2...        1000        1...       8888       4444        5555       3333
           1102        0001       00.1       ...2        0001        ...1       8889       4444        5555       3333
 ORIG    0.          0.          0.         0.          0.          0.         0.          0.          0.          0.
 UNITS   100.        300.        300.       800.        500.        .150E+04   .600E-01    2.00        5.00        5.00
 TOTAL   .686E+04    .147E+05    .866E+04   .198E+05    .234E+05    .432E+05   20.1        399.        .113E+04    828.
  CENTRE POINT OF GRAZING ACTIVITIES  2.29 3.82 DISPERSAL    4.571
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::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
 SUMMARY FOR  1-12- 1-   335. DAYS OF RUN  90. DAYS SINCE THE LAST SUMMARY
 SHEEP NUMBERS   265.     BODY WEIGHT  42.9 KG     WOOL WEIGHT  2.35 KG        CELLS  37      SPECIES   5    GROUPS  10
 TOTAL RF   153.5 MM   NO. OF WET DAYS   28 .... OR   68.0 MM AND            WOOL LENGTH  70. MM
                                                              12 DAYS SINCE THE LAST SUMMARY.   MEAN DAY TEMP.   21.0 C
          GRASS
                              BASSIA
                                                 STANDING DEAD
                                                                        ATRIPLEX VESICARIA
                                                                                              KOCHIA SEDIFOLIA  335.

          371. 355. 310.
 364. 336. 380. 356. 325.
 352. 314. 366. 338. 311.
 330. 309. 327. 369.
 293. 353. 327. 322.
 203. 346. 330. 379.
 364. 288. 379. 372.
 329. 336. 331. 350.
 341. 339. 427. 412.
 BIOM TOTAL   808.7 TONNES
 CONS TODAY    .482
 CONS MEAN     .645

           209. 204. 189.
 208. 198. 212. 205. 195.
 205. 190. 209. 199. 189.
 209. 191. 197. 212.
 197. 214. 199. 197.
 184. 214. 205. 217.
 211. 204. 217. 215.
 201. 202. 201. 207.
 202. 202. 231. 230.
                483.9
                 .140
                 .196

            102.  99.  90.
 100.  95.  103.  99.  93.
  98.  91.  101.  95.  90.
  94.  90.   93. 101.
  87.  99.   93.  92.
  70.  97.   94. 104.
 101. 106.  104. 102.
  94.  95.   94.  98.
  96.  96.  112. 110.
                229.1
                 .026
                 .019

            190.  22. 115.
 208. 161.   34.  89.  22.
 311. 106.  306.  22.  21.
 168. 233.  138. 219.
  87. 189.  198. 116.
   0. 114.  184. 197.
 322. 202.  314. 228.
 430. 181.   53. 129.
 337. 192.   93. 308.
                399.5
                 .070
                 .103

            141. 218. 419.
 160. 272.  155. 206. 336.
 178. 373.  128. 287. 414.
 262. 424.  293. 129.
 304. 120.  271. 294.
 603. 163.  233.  98.
 117. 121.   65. 108.
 293. 223.  248. 193.
 198. 222.   34.   0.
               531.4 TOT 2452.7
                .016 TOT   .734
                .024 TOT   .987

 GRAZING TIME  7.22 HOURS       WALKING  7.62 KM       DRINKING  2.63 LITRES PER SHEEP PER DAY
 SHEEP DRANK   306 TIMES IE  .90 TIMES EACH, PER DAY   .... HOURLY DISTRIBUTION:
 0.0000.0000.000 .098   .107 .049 .002 .019   .016 .025 .024 .015   .041 .047 .036 .043   .051 .056 .161 .197   .006 .011 .0060.000
 0.0000.0000.000 .066   .119 .133 .137 .116   .100 .058 .030 .015   .008 .013 .021 .033   .054 .077 .0210.000  0.0000.0000.0000.000
    6497.

 ACTIVITIES ETC
      GRAZE      ACCUM  REST/TRAV  SH/CMP/DR    EXTEN.     TOTAL    NITRATE     SM 1     SM 2     SM 3

       ...
      .....
      .....
      000.
      2100
      8200
      6600
      0000
      0001

       ...
      .....
      .....
      6000
      2200
      7210
      6700
      1000
      0001

       ...
      0....
      .....
      00..
      0000
      9110
      0100
      1...
      00.1

       ...
      0..0.
      .....
      ....
      ....
      803.
      ....
      1...
      ...1

       ...
      0....
      .....
      0000
      1100
      8110
      0400
      1000
      0001

       ...
      0..0.
      .....
      ....
      00..
      601.
      .0..
      1...
      ...1

       777
      77777
      77777
      7777
      7777
      8777
      7777
      7777
      7777

       555
      55555
      55555
      5555
      5555
      5555
      5555
      5555
      5555

       555
      55555
      55555
      5555
      5555
      5555
      5555
      5555
      5555

       333
      33333
      33333
      3333
      3333
      3333
      3333
      3333
      3333

 ORIG    0.        0.        0.        0.        0.        0.        0.        0.        0.        0.
 UNITS   150.      400.      400.      .150E+04  800.      .300E+04  .800E-01  2.00      5.00      5.00
 TOTAL   .650E+04  .212E+05  .126E+05  .310E+05  .339E+05  .649E+05  23.3      469.      .112E+04  762.
  CENTRE POINT OF GRAZING ACTIVITIES   2.05 3.87 DISPERSAL   3.784
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:::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::
 SUMMARY FOR  1- 3- 2-   425. DAYS OF RUN  90. DAYS SINCE THE LAST SUMMARY
                                                                          CELLS  37    SPECIES   5    GROUPS  10
 SHEEP NUMBERS   279.     BODY WEIGHT  41.4 KG     WOOL WEIGHT  3.10 KG     WOOL LENGTH  93. MM
 TOTAL RF   197.5 MM   NO. OF WET DAYS   32 .... OR   44.0 MM AND    4 DAYS SINCE THE LAST SUMMARY.    MEAN DAY TEMP.    24.0 C

            GRASS                        BASSIA                    STANDING DEAD              ATRIPLEX VESICARIA           KOCHIA SEDIFOLIA  425.

            203. 196. 176.                72.  70.  64.             377. 364. 328.                 193.  23. 116.               143. 222. 424.
200. 188. 207. 197. 183.   71.  67.  73.  70.  66.   372. 349. 384. 365. 340.   212. 163.  35.  91.  22.   163. 276. 158. 209. 341.
195. 178. 201. 188. 177.   70.  64.  71.  67.  64.   363. 331. 373. 350. 329.   315. 107. 311.  22.  21.   181. 377. 130. 291. 419.
185. 176. 182. 201.        68.  65.  66.  72.        346. 328. 341. 375.        170. 234. 139. 222.        266. 428. 297. 131.
164. 189. 183. 180.        66.  73.  68.  66.        317. 362. 343. 338.         86. 189. 199. 117.        308. 122. 275. 298.
120. 186. 185. 205.        62.  73.  70.  75.        248. 357. 347. 385.          0. 113. 185. 200.        606. 166. 237. 100.
200. 159. 205. 203.        72.  69.  75.  74.        373. 324. 384. 379.        326. 198. 318. 232.        119. 123.  66. I10.
184. 186. 186. 194.        68.  69.  68.  71.        346. 350. 347. 362.        432. 182.  54. 131.        296. 226. 252. 196.
190. 189. 226. 220.        69.  69.  80.  80.        354. 353. 422. 412.        341. 195.  96. 314.        201. 226.  35.   0.
 BIOM TOTAL  447.5 TONNES              164.8                      839.8                      403.7                     538.6 TOT 2394.5
 CONS TODAY    .610                    .107                       .198                       .248                      .043 TOT  1.206
 CONS MEAN     .573                    .133                       .103                       .110                      .028 TOT   .946

 GRAZING TIME  6.81 HOURS     WALKING  7.64 KM     DRINKING  2.94 LITRES PER SHEEP PER DAY
 SHEEP DRANK  886 TIMES IE  .98 TIMES EACH, PER DAY    .... HOURLY DISTRIBUTION:
0.0000.0000.000 .137   .065 .008 .003 .009   .014 .009 .017 .032   .047 .047 .062 .058   .059 .081 .088 .159   .037 .023 .017 .028
0.0000.0000.000 .115   .132 .136 .138 .119   .081 .033 .013 .005   .003 .005 .011 .017   .044 .079 .0680.000   0.0000.0000.0000.000
    6126.

 ACTIVITIES ETC
          GRAZE      ACCUM REST/TRAV SH/CMP/DR    EXTEN.     TOTAL   NITRATE      SM 1       SM 2       SM 3
           ...        ...       ...        ...        ...       ...        444       222        666        333
          .....      .....     .....      0..0.      .....     0..0.     44444     22222      66666      33333
          .....      .....     .....      .....      .....     .....     44444     22222      66666      33333
          0000       0000      00..       ....       00..      ....      4444      2222       6666       3333
          2200       3200      000.       ..0.       1000      000.      5554      2222       6666       3333
          7210       8310      8110       802.       6100      912.      7554      2222       6666       3333
          .400       0700      00..       ....       0200      .1..      4554      2222       6666       3333
          000.       1000      0...       1...       0000      1...      5444      2222       6666       3333
          0..0       0001      0..0       ...1       0..0      ...1      4455      2222       6666       3333
 ORIG    0.          0.         0.         0.         0.         0.         0.         0.         0.         0.
 UNITS   150.        500.       600.       .200E+04   .150E+04   .300E+04   .100E+00   2.00       5.00       5.00
 TOTAL   .613E+04    .274E+05   .163E+05   .428E+05   .437E+05   .864E+05   20.5       253.       .126E+04   681.
  CENTRE POINT OF GRAZING ACTIVITIES   2.14 4.12 DISPERSAL   3.640
  MEAN TIME PER DAY OF SIMULATION    .161 SECS.
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::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::::

 SUMMARY FOR  6- 3- 2-   430. DAYS OF RUN    5. DAYS SINCE THE LAST SUMMARY
                                                                           CELLS  37     SPECIES    5     GROUPS  10
 SHEEP NUMBERS   279.      BODY WEIGHT  41.4 KG       WOOL WEIGHT    .10 KG     WOOL LENGTH    2. MM
 TOTAL RF   197.5 MM    NO. OF WET DAYS    32 .... OR     0.0 MM AND     0 DAYS SINCE THE LAST SUMMARY.    MEAN DAY TEMP.    20.1 C

            GRASS                             BASSIA                          STANDING DEAD               ATRIPLEX VESICARIA              KOCHIA SEDIFOLIA  430.

             185. 178. 160.                         65.  63.  57.                      388. 375. 338.                  193.  23. 116.                   143. 222. 424.
 182. 171. 185. 179. 166.       64.  61.  66.  63.  59.   383. 360. 395. 376. 351.   212. 163.  35.  91.  22.   163. 276. 158. 209. 341.
 177. 152. 193. 171. 161.       63.  58.  64.  61.  57.   373. 341. 384. 361. 339.   315. 107. 311.  22.  21.   181. 377. 130. 291. 419.
 169. 166. 165. 183.            61.  58.  60.  65.        357. 338. 351. 386.        170. 234. 139. 222.        266. 428. 297. 131.
 149. 172. 167. 164.            60.  66.  61.  60.        327. 373. 353. 348.         86. 189. 199. 117.        308. 122. 275. 298.
 108. 159. 164. 188.            56.  66.  63.  63.        255. 367. 357. 396.          0. 113. 185. 200.        606. 166. 237. 100.
 182. 144. 187. 185.            65.  63.  67.  66.        385. 333. 396. 390.        326. 198. 318. 232.        119. 123.  66. 110.
 168. 170. 169. 176.            62.  62.  62.  64.        356. 360. 358. 373.        432. 182.  54. 131.        296. 226. 252. 196.
 172. 172. 205. 201.            62.  62.  72.  72.        365. 364. 435. 424.        341. 195.  96. 314.        201. 226.  35.   0.
  BIOM TOTAL   406.9 TONNES                 148.6                         864.7                    403.6                        538.6 TOT 2362.4
  CONS TODAY   0.000                        0.000                         0.000                    0.000                        0.000 TOT   0.000
  CONS MEAN    0.000                        0.000                         0.000                    0.000                        0.000 TOT   0.000

  GRAZING TIME   0.00 HOURS       WALKING   0.00 KM       DRINKING   0.00 LITRES PER SHEEP PER DAY
  SHEEP DRANK      0 TIMES IF 0.00 TIMES EACH, PER DAY     .... HOURLY DISTRIBUTION:
      I    I    I    I      I    I    I    I      I    I    I    I      I    I    I    I      I    I    I    I      I    I    I    I
      I    I    I    I      I    I    I    I      I    I    I    I      I    I    I    I      I    I    I    I      I    I    I    I
        0.

  ACTIVITIES ETC
          GRAZE       ACCUM   REST/TRAV  SH/CMP/DR     EXTEN.      TOTAL     NITRATE      SM 1        SM 2        SM 3
                       ...       ...        ...          ...        ...        444         222         666         333
                      .....     .....      0..0.       .....      0..0.      44444       22222       66666       33333
                      .....     .....      ....-.      .....      .....      44444       22222       66666       33333
                      0000      00..       ....        00..       ....        4444        2222        6666        3333
                      3200      000.       ..0.        1000       000.        5554        2222        6666        3333
                      8310      4110       802.        6100       912.        7554        2222        6666        3333
                      6700      00..       ....        0200       .1..        4554        2222        6666        3333
                      1000      0...       1...        0000       1...        5444        2222        6666        3333
                      0001      0..0       ...1        0..0       ...1        4455        2222        6666        3333
 ORIG      0.         0.        0.         0.          0.         0.          0.          0.          0.          0.
 UNITS     0.         500.      600.       .200E+04    .150E+04   .300E+04    .100E+00    2.00        5.00        5.00
 TOTAL   681.         .274E+05  .163E+05   .428E+05    .437E+05   .864E+05    20.5        235.        .124E+04    678.
  CENTRE POINT OF GRAZING ACTIVITIES   0.00 0.00 DISPERSAL    0.000
  MEAN TIME PER DAY OF SIMULATION     .023 SECS.

 ********************************************************************************************************************
    SHEARING OCCURS
    CLIP PER SHEEP   3.00 KG --- TOTAL FOR FLOCK    838.11 KG
  21. SHEEP DIED SINCE THE PREVIOUS SHEARING.
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