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WORLD METEOROLOGICAL ORGANIZATION

TECHNICAL NOTE No. 190

WEATHER, CLIMATE AND ANIMAL PERFORMANCE

by
J. R. Starr

(CAgM Rapporteur on Weather and Climate and Animal Performance)

WMO - No. 684

Secretariat of the World Meteorological Organization - Geneva - Switzerland

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WMO

The World Meteorological Organization (WMO), of which 160 States and Territories are Members, is a specialized agency of the United Nations.

It was created:

- To facilitate world-wide co-operation in the establishment of networks of stations for making meteorological observations as well as hydrological and other physical observations related to meteorology, and to promote the establishment and maintenance of centres charged with the provision of meteorological and related services;
- To promote the establishment and maintenance of systems for the rapid exchange of meteorological information;
- To promote standardization of meteorological and related observations and to ensure the uniform publication of observations and statistics;
- To further the application of meteorology to aviation, shipping, water problems, agriculture and other human activities;
- To promote activities in operational hydrology and to further close co-operation between Meteorological and Hydrological Services;
- To encourage research and training in meteorology and, as appropriate, in related fields, and to assist in co-ordinating the international aspects of such research and training.

The machinery of the Organization consists of the following bodies:

The *World Meteorological Congress*, the supreme body of the Organization, brings together the delegates of all Members once every four years to determine general policies for the fulfilment of the purposes of the Organization, to adopt Technical Regulations relating to international meteorological practice and to determine the WMO programme.

The *Executive Council* is composed of 36 directors of national Meteorological or Hydrometeorological Services. It meets at least once a year to conduct the activities of the Organization, to implement the decisions taken by its Members in Congress and to study and make recommendations on any matter affecting international meteorology and related activities of the Organization.

The six *regional associations* (Africa, Asia, South America, North and Central America, South-West Pacific and Europe), which are composed of Member Governments, co-ordinate meteorological and related activities within their respective Regions and examine from the regional point of view all questions referred to them.

The eight *technical commissions*, consisting of experts designated by Members, are responsible for studying any subject within the purpose of the Organization. Technical commissions have been established for basic systems, instruments and methods of observation, atmospheric sciences, aeronautical meteorology, agricultural meteorology, marine meteorology, hydrology, and climatology.

The *Secretariat*, located at 41 Avenue Giuseppe-Motta, Geneva, Switzerland, is composed of a Secretary-General and such technical and clerical staff as may be required for the work of the Organization. It undertakes to serve as the administrative, documentation and information centre of the Organization, to make technical studies as directed, to support all the bodies of the Organization, to prepare, edit or arrange for the publication and distribution of the approved publications of the Organization, and to carry out duties allocated in the Convention and the regulations and such other work as Congress, the Executive Council and the President may decide. The Secretariat works in close collaboration with the United Nations and its specialized agencies.

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FOREWORD

Meteorological information is of economic value to agriculture only if it is received by managers and decision-makers in time and in a suitable form for translation into profitable action. Its effective application is contingent upon the user's knowledgeable understanding of the relationships between meteorology and agriculture.

The success of the world campaign against hunger depends not only on increasing crop production but also on raising the productivity of livestock. WMO Technical Note No. 168 - The Role of Agrometeorology in Agricultural Development and Investment Projects (WMO-No. 536, 1980) - highlighted the value of taking weather and climate information into account at all stages of agricultural investment and development projects. The eighth session of the Commission for Agricultural Meteorology (Geneva, 1983) emphasized the need to concentrate on the role of weather-based decisions in the management and economics of livestock production and appointed a rapporteur to review and provide examples and case-studies to further document the role of meteorology in these endeavours. This present Technical Note constitutes the work of the rapporteur.

I should like to take this opportunity to express the gratitude of WMO to Dr J. Starr (United Kingdom) for the time and effort he has devoted to preparing this publication, which I consider to be of great benefit to all concerned with increasing livestock production.

(G.O.P. Obasi)
Secretary-General

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SUMMARY

Various organizations and disciplines concerned with animal studies have come to appreciate the role of meteorology in their field. An International Veterinary Students' Association seminar held in Geneva in 1983, whose subject was co-operation for the control of animal diseases, had as one of its objectives to inform participants of the "contribution of other disciplines whose role is not always immediately apparent (e.g. meteorology) ..... to the improvement of the management of animal health and production".

The first chapter of this Technical Note discusses the relevant management principles as well as the direct and indirect factors which limit production.

The second chapter proposes examples of weather-based decisions in the management and economics of livestock production for inclusion in the curricula of training programmes.

Chapter 3 provides guidelines for operational measures and other programmes to be adopted by extension services with agrometeorological support.

Appendixes A to E give specific examples of strategic and tactical decision-making and identify existing shortcomings in terms of techniques and data. The implications of these limitations for decision-making are assessed and areas for research and development proposed.

RESUME

Divers organismes et disciplines qui s'occupent d'études zootechniques s'intéressent aujourd'hui au rôle que la météorologie joue dans leur domaine. Un cycle d'étude de l'Association internationale des étudiants vétérinaires, qui s'est tenu à Genève en 1983 et qui traitait de la coopération dans la lutte contre les maladies des animaux, avait notamment pour objectif d'informer les participants de la "contribution d'autres disciplines dont on ne voit pas toujours immédiatement le rôle (c'est le cas par exemple de la météorologie) ... dans l'amélioration de la gestion de la santé et de la production animales".

Le premier chapitre de la présente note technique examine les principes pertinents de gestion ainsi que les facteurs directs et indirects qui entravent la production.

Le deuxième chapitre propose des exemples de décisions en matière de gestion et d'économie de la production animale prises en fonction des conditions météorologiques, qui pourront figurer au programme des cours de formation.

Le chapitre 3 présente des directives concernant les mesures pratiques et les programmes que doivent adopter les services de vulgarisation qui bénéficient d'un appui agrométéorologique.

Les appendices A à E donnent des exemples précis de prises de décisions stratégiques et tactiques et mettent en évidence les lacunes existantes en ce qui concerne les techniques et les données. Les incidences qu'ont ces lacunes sur la prise de décisions sont évaluées, et des domaines de recherche et de développement sont proposés.

РЕЗЮМЕ

Различные организации и отрасли науки, связанные с изучением животных, пришли к пониманию роли метеорологии в этой области. Проведеный в 1983 г. в Женеве семинар Международной ветеринарной студенческой ассоциации, предметом которого было сотрудничество в борьбе с болезнями животных, имел одной из своих целей информирование участников о "вкладе других дисциплин, роль которых не всегда очевидна (например, метеорология), ... в улучшение управления здоровьем и продуктивностью животных".

В первой главе настоящей технической записки излагаются соответствующие принципы управления, а также прямые и косвенные факторы, которые ограничивают производство.

Во второй главе предлагаются примеры принятия решений, основанные на учете погоды в управлении и в экономике производства животноводческой продукции, которые предназначены для включения в учебные курсы программ подготовки кадров.

В третьей главе даются руководящие принципы текущей работы и других программ для принятия их службами популяризации агрометеорологических знаний.

В приложениях А-Е содержатся конкретные примеры принятия стратегических и тактических решений, а также указываются недостатки, существующие в методиках и информации. Оценивается влияние этих ограничений на принятие решений, и предлагаются области для научных исследований и разработок.

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RESUMEN

Diversas organizaciones y medios disciplinarios que se ocupan de estudios zootécnicos han comenzado a interesarse en la función que desempeña la meteorología en sus respectivos ámbitos de competencia. Un seminario de la Asociación Internacional de Estudiantes de Veterinaria, celebrado en Ginebra, en 1983, que versó sobre la cooperación para el control de las epizootias, tuvo, entre otros, objetivos, el de informar a los participantes sobre la "contribución de otras disciplinas, cuya función no siempre se advierte de un modo inmediato (por ejemplo, la meteorología) en la mejora de la atneción de la salud animal y la gestión de la producción pecuaria".

En el primer capítulo de la presente Nota Técnica se abordan los correspondientes principios de gestión así como los factores directos e indirectos que influyen en la producción.

En el segundo capítulo se dan ejemplos de decisiones adoptadas en función del tiempo para la gestión y economía de la producción pecuaria con el fin de incluirlos en los programas de estudio de formación profesional.

El Capítulo 3 proporciona directrices sobre medidas operativas y programas que podrán adoptar los servicios de divulgación agraria apoyándose en la agrometeorología.

En los Apéndices A a E se exponen ejemplos concretos de adopción de decisiones estratégicas y tácticas y de identificación de las deficiencias existentes en función de las técnicas y datos disponibles. Se evalúan las consecuencias de estas limitaciones en la adopción de decisiones y se proponen esferas de investigación y desarrollo.

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CHAPTER 1

WEATHER, CLIMATE AND ANIMAL PERFORMANCE

1.1 Introduction

Animal production plays an important role in the agriculture of many areas but the penalties incurred from livestock vulnerability to certain - but not necessarily severe - environmental conditions, can be significant. For example, the arid zones contain over one-half of the world's cattle, more than a third of its sheep and two-thirds of its goats, yet livestock productivity in the developing countries - many of which lie wholly or mainly in the arid zones - is only 10 to 20 per cent of that achieved in the more technologically advanced and climatically favoured regions (Richards, 1981; Dorman, 1981). Similarly, despite the tremendous potential for animal production in the tropics there is a vast disparity compared with more temperate zones due in large measure to the impact of animal diseases which continually undermine any significant production programmes. For instance, animal productivity in Latin America and the Caribbean is only 67 per cent of that of Australia and 37 per cent of that of the USA. Animal diseases are estimated to account for some 35 per cent of productivity losses in livestock in tropical America (Arambulo and Moran, 1981).

This high incidence of animal disease in the tropics stems primarily from the simultaneous occurrence of both temperate zone and tropical zone diseases, as well as the hospitable conditions for rapid transmission of disease. Clearly, there are many causes of different production rates in different parts of the world, but relationships between weather, climate, animal health and performance must be understood if production is to be predicted and the outcome influenced by management action (Maunder, 1977).

1.1.1 The meteorologists' responses

In order to be involved in any long-term livestock investment decisions and strategies, meteorologists need to understand how their data can be converted to useful inputs for risk analyses. Examples of meteorological inputs to such investment decisions are given by Omar (WMO, 1980(a)) and by Robertson (WMO, 1980(b)) and risk analysis is discussed in Chapter 7 of the WMO Guide to Agricultural Meteorological Practices (WMO, 1981). Tactically, the understanding of the interaction between the animal and its environment may require interdisciplinary "on site" monitoring of the environment and the development of techniques to warn of incipient stress and attendant production losses. Weather information has to be tailored to livestock purposes (WMO, 1981).

1.2 Management perspectives

Management for improved livestock production requires many resources (Figure 1.1) and, in guiding strategies and tactics for livestock management, the following questions must be asked:

(a) What is the climatic impact on production - on the animals directly and on the availability of their basic feed?

(b) Can adverse effects be countered to encourage optimum production or are there other limiting factors such as poor management, poor pastures or parasites (as Michael (1984) suggests is likely in the tropics)?

If weather and climate are the major factors limiting production (Figure 1.2), this understanding must be translated into economic terms by asking:

(a) By how much and how often does climate depress productivity?;

(b) What is the cost and benefit of ameliorating climate, for example, by adjusting management or by investment in on-farm structures (buildings, dips, etc.)?;

(c) What are the management and economic penalties if protective measures are not taken? (Smith, 1974; Maunder, 1977; WMO, 1980(a); and Johnson, 1982).

1.2.1 Management for animal production

Successful application of such weather and climate information to guide management decisions will require detailed inputs of:

(a) The extent to which livestock response (i.e. feed intake, growth and reproduction, productivity, etc.) is known to be related to meteorological factors and the observable physiological consequences such as deep body temperature or animal behaviour;

(b) The likely occurrence of the critical weather factors affecting this response (Hahn, 1981).

1.2.2 Other factors in production studies

When studying the responses of animal production systems to weather and/or climate, account has also been taken of factors which are not functions of the physical environment. Thus, management efficiency, husbandry methods and the social behaviour of the animal will all play a role.

These points are summarized as follows:

(a) Animals are not machines but have certain drives and behavioural and physiological responses to the environment;

(b) Livestock production is an economic activity;

(c) Managers will respond differently to changing conditions.

The implications of factor (a) are, for example, that although the environment may determine the rate of heat loss of the animal, some control over microclimates may be achieved by group or individual behaviour. Indeed, stock can also compensate to some degree for depressed growth under short-term stress. Economic aspects (b) imply that performance must be measured in economic terms - in light of the availability of resources, energy and of benefits derived per unit cost. In (c) the response will depend on the manager's ability to decide among alternatives and then act on those decisions.

For the producer, adviser and research worker, the imposition of political policies on livestock production can represent further uncontrollable factors superimposed on the purely physical hazards (Smith, 1975).

1.2.3 The influence of weather and climate

Weather and climate can determine the efficiency of livestock production by influences that are both direct and indirect and that affect health, reproductive efficiency, productive conversion of feed and, indeed, the very survival of the animal - particularly at critical stages of the life cycle. Direct influences affect the heat balance of the animal and will also include extreme events (such as floods) that affect survival. Indirect influences affect land use and management, feed production and conservation, waste disposal, disease and parasites.

1.2.4 Constraints on management

Directly or indirectly, these influences represent constraints on the management options open to farmers. Assuming that feed is available, the extent to which a constraint limits production in a particular climate or environment will depend on breed, individual physiological characteristics and the intensity of farming operations. Thus, some farmers may choose to operate intensively near the extreme limit of weather risks, investing heavily in protective or corrective measures. Others will operate less intensively and well within the limits of weather factors. The choice depends on individual ambition, management skills and capital.

1.2.4.1 Rational planning to meet constraints

Rational planning implies a positive search for alternatives with adequate strategic facts providing a basis for the rational selection and the objective planning for efficient production. Managers should be able to decide among alternatives to maximize gain or, at least, minimize loss. Hahn (1981) illustrates in a decision tree (Figure 1.3) the factors leading from environmentally induced production events to a management decision. He remarks, however, that each manager will still apply such information differently and, furthermore, that his decisions are often shaped by retrospective experience.

1.2.4.2 Information for rational planning

Rational management must then be based on information about the physiology of the animal, the production system and the environment. These requirements are dealt with in more detail in Appendix A.

1.3 Housing management to reduce weather and climate impact on livestock production

1.3.1 Economics of environmental control

Assessment of the economic contribution of controlling the environment requires meteorological data to assess the penalties of departing from the optimum conditions taking account of potential economic returns, energy cost and availability. In many parts of the world, the opportunity for environmental modification for improving production may prove limited

(McDowell, 1972), being uneconomic, beyond local management and energy resources or being less important than optimizing other constraints (e.g. parasitic burdens).

1.3.2 The thermal environment

Livestock are usually housed because thermal imbalance results in adverse effects on productivity (to an extent depending on feed level), physiology, breed and the stage in the life cycle (Smith, 1972; Starr, 1981; Sivanappan and Natarajan, 1984; and Keane, 1986).

1.3.2.1 Thermo-neutral zone

The term is open to a number of interpretations but in this case refers to the range of air temperatures within which heat production is not affected by air temperature (Figure 1.4). It corresponds approximately to the zone of thermal comfort and optimal feed utilization. The boundaries of the zone are termed the upper and lower critical temperatures. In ruminants, the lower critical temperature is the more likely to be of practical interest in the temperate zones and the upper critical temperature in hot climates. Any reference to critical temperatures must take account of the environment to which the animals are normally exposed; previous conditioning affects coat cover and metabolic intensity. Thus, animals accustomed to very cold conditions have a greater cold tolerance than those which are not.

1.3.2.2 General guide to housing requirements

General guidelines are available for long-term exposure to climate for various categories of livestock resulting in only nominal losses in production (Table 1.1). The generalizations can be helpful but they are not specific enough to provide the basis for housing and management decisions. This will need information on cost of housing, feed, labour, the product price and the expected frequency of climatic impacts on production. Not all modifications of management or housing will be profitable, or indeed acceptable, and optimum environments for maximum production may not be optimum in economic terms.

1.3.3 Veterinary aspects - synopsis of the UK experience

Most diseases of housed cattle and sheep cause chronic lesions that cannot be treated successfully, there being no effective vaccines. Therefore, prevention is all-important, and for most diseases this involves the ability to provide clean, well-ventilated buildings to keep various bacteria and viruses down to a level at which the animals' natural defences can cope easily. The multidisciplinary approach to preventive medicine is all-important, and all the available sources of advice to the farmer must be consulted when buildings are to be erected or modernized.

1.3.3.1 Cattle

Calves kept indoors are very prone to pneumonia and enteric conditions, many losses being precipitated by the artificial environment created by housing. Of all calves born in the UK, 5 per cent die in the first month, and about 10 per cent of these deaths are due to respiratory disease. Respiratory disease becomes increasingly more prevalent, however, with age, causing approximately 60 per cent of losses in beef cattle from one month of age to slaughter. The resultant overall reduction in liveweight gain (and figures quoted appear to range from 2 to 7.5 per cent during an outbreak of respiratory disease), together with the cost of medication, can lead to large losses. The bovine lung seems to be more susceptible to pneumonia and allergic reactions than that of other animals. Ventilation and calf-housing therefore have to aim at preventing the build-up of a whole host of different agents such as viruses, bacteria, dust and gases, which can affect the lung and cause death.

1.3.3.1.1 Calf pneumonia (see 1.5.3)

Because of the multiplicity of agents involved and the usual chronic nature of the condition, therapy with antibiotics is usually of limited success. (There is still no effective treatment for viral diseases.) Control and prevention must then come from good housing with adequate ventilation so that the lung irritants, both infectious and inanimate, are removed before they can cause further problems. An example of recommended design data for cattle in the UK is illustrated in Table 1.2 and Figure 1.5.

1.3.3.1.2 Mature animals

Adult animals are fairly resistant to both bacterial and viral conditions, but *E. coli* - or coliform mastitis - is becoming an increasing problem in housed dairy cows. This arises from contamination of the udder with dung and slurry. Basic hygiene and strict management of the milking herd are important, but two environmental factors also need consideration:

(a) If a cubicle house is poorly ventilated, warm moisture-laden air readily condenses in the roof and timber and drips down, making bedding damp and allowing organisms to multiply;

(b) Observation on the behaviour of dairy cows has shown that, if a building is too cold and draughty, or the ambient temperature is too low, cows will spend much more time lying down and, in effect, incubate their bedding, increasing its coliform organism count.

1.3.3.2 Sheep

Of the 16.7 million lambs born in the UK each year, nearly three million die (i.e. a 17 per cent mortality rate). To this can be added the 1.4 million ewes that die each year, making a total of 4.4 million sheep lost annually. Similarly, large or excessive percentage losses are reported from other European countries and Australasia (Slee, 1985). Intensive veterinary input in disease control makes very little impact on these figures, as most of the losses occur during the short hectic period around lambing, when shepherds are fully occupied. Improvement in these figures must, therefore, come from management aids and provision of shelter over the lambing period. (Veterinary input does have an effect on the ewe mortality figures, thus a programme of vaccination, anthelmintic dosing and general management considerations of feeding and body condition can prolong their productive lives.) The principles of housing management are explored in Appendix B, beginning with a simple model illustrating housed livestock production.

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1.4 Stress

1.4.1 Definitions

Those involved in animal husbandry commonly use the term "stress" to indicate "an environmental condition adverse to the animal's well-being" (Stott, 1981). The origin may be climatic, nutritional, physiological, social, or indeed, a combination of these. In addition to ongoing conditions, the requirement to accommodate to a sharp or sudden change (perhaps in a matter of hours) to any of these factors of "total environment" of the animal will also constitute a stress. For example, both the close confinement of animals (as in some long-term housing) and their short-term confinement (as when they are carried on trucks to market) will constitute a stress (Smith, 1975). Either may lay the animal open to opportunistic infection associated with synergistic effects.

Nevertheless, it must be noted that stress may also encourage protection against infection through activation of body immune response reactions (Kelley, 1980; Kelley and Blecha (in preparation)).

1.4.1.1 Direct stresses

There are obvious dramatic "direct" stresses such as lightning strikes, droughts, floods, blizzards, etc., whose potential danger can be offset or alleviated by the combination of tailor-made weather forecasts and good husbandry, e.g. shepherding in anticipation of blizzards. (Floods can encourage disease indirectly by disseminating micro-organisms such as anthrax and clostridial spores.) Other direct stresses are due to the upsetting of the animal's heat balance, examples of which are presented in Appendix C. The influences of weather extremes on livestock health and fertility are reviewed by Hugh-Jones and Yvoré (in preparation).

1.4.1.2 Indirect stresses

Any disturbances that stress the animal are likely to encourage disease. Thus, viral, bacterial, parasitological and metabolic factors can all induce "indirect" stresses. Appendix C discusses weather-based predictions of some stress-induced animal health problems; viral and parasitological diseases are the subject of the next two sections and Appendixes D and E.

1.5 Airborne infection

1.5.1 Infectious diseases

All animals co-exist with a mass of potentially pathogenic micro-organisms so that infection may be said to be the natural state and disease simply the result of a loss of equilibrium between host, micro-organism and the environment. The extent to which this holds true depends on the nature of the disease; thus the aetiology of respiratory diseases is particularly complex (see 1.3.3.1.1).

1.5.2 Pathogen generation and transport

The generation and dispersal of aerosols of such pathogens occur through the processes of breathing, coughing, sneezing, defecating, skin sloughing, hosing down and slurry spreading (Pedgley, 1982; Wathes et al., 1983). Meteorological and other factors influence the viability of the virus and the transport, dispersion and deposition of the aerosol cloud (Chamberlain, 1967). An understanding of these processes could be used to prevent or control disease (Donaldson, 1978). Appendix B enlarges on these aspects. Certain diseases transmitted by the airborne route are listed in Table 1.3 (Falk and Hunt, 1980).

1.5.3 Impact of weather on infectious disease initiation

The impact of meteorological factors in initiating infectious diseases involves a complex interaction of environmental influences, their intensity and duration, with animal immune responses, as well as management and genetic factors. These interactions are still imperfectly understood. Indeed, each incident involves a number of infectious agents, with the predominant organism often changing two or more times during any outbreak. It is unusual for a simple organism to be involved. Certainly it is extremely difficult to reproduce clinical disease by experimental infection even when mixed organisms are used (Omar, 1966) and multivalent vaccines have not been successful in reducing the incidence of infectious disease in calves (Morzaria et al., 1978).

Yet it is generally acknowledged that the incidence and severity of enteric and respiratory diseases - at least in cattle - are influenced by environmental stresses, particularly those associated with weather, overcrowding, mixing age groups (and hence exposure to different pathogenic organisms) and post-natal stress. Not surprisingly, there have been few attempts to analyse this complex interaction. Webster (1981), however, attempted to pull together isolated research items and to provide some coherent designs for future investigation. He postulated a logical approach to evaluate the possible contribution made by weather to the pattern of disease in a particular clinical situation and listed the major factors that determine the impact of the weather on infectious disease in animals (Table 1.4). The first heading of the table deals with biometeorological stimuli. The first group of these, "thermic stimuli", primarily concerns sensations of heat and cold; this is obviously an incomplete definition. The second group of stimuli, humidity, barometric pressure, ionization and pollution, have nothing in common except that they have little or no direct thermal effect on the animal. The third group, "change", is a deliberately non-specific concept which recognizes that any alteration to the external environment constitutes a stimulus to homeostasis and that many aspects of an animal's response are common to all types of sudden environmental change (see 1.4.1).

1.5.4 Spread of secondary infections

Mathematical and physical models can be used to monitor the potential spread of secondary infections of a variety of airborne diseases, e.g. foot-and-mouth disease. The application of these mathematical diffusion models has also led to recommendations for the spacing of housing and the critical stocking densities of certain classes of livestock and has proved their worth operationally (see Appendix D).

1.6 Parasitism

1.6.1 Parasites and production

Animal parasitic diseases bring about a world-wide reduction in productivity not only directly, through loss of liveweight gain, milk, eggs and progeny, but also indirectly through longer and less efficient production cycles and poorer quality of produce (Gibson, 1978; Table 1.5). Studies on ticks, parasitaemias, fascioliasis and gastro-enteric helminthiasis indicate that the economic penalties are large and significant, particularly in the tropics where transmission of parasitic helminths can take place throughout the year (Table 1.6; Hadani et al., 1971; Pugh et al., 1980; Arambulo and Moran, 1981; El Azazy and van Veen, 1983).

It is now recognized that the control of parasitic diseases is not simply dependent on good management and the use of parasiticides, but also on the proper timing of the preventive and remedial measures; it is here that meteorology and the accurate forecasting of disease incidence can play a significant part in better disease control.

Gibson (1978) demonstrated that accurate forecasting of animal parasitism with the help of meteorological data was already possible for a number of diseases. The benefits from interdisciplinary co-operation are not just economic in nature but have, in some cases, resulted in an expansion of knowledge of the biology of the various parasites, the epidemiology of the associated diseases and the increased exploitation of genetic resistance. The latter is particularly important for developing countries where conventional disease control is often non-existent or ineffective for reasons of manpower or economy (Murray et al., 1984).

1.6.2 Parasitic disease incidence forecasts

The study of the transmission of parasitic diseases among grazing animals and its relation to climatic factors offers a realistic approach to the control of many animal diseases and, hence, to potential gains in productivity (Gettinby and Gardiner, 1980). Macleod (1939) made an early reference to this approach when he observed that tick activity increased with weekly mean maximum air temperature, while Gordon (1948) correlated many field and laboratory studies into a "climatic profile" (Figure 1.6) to present a rationale for the geographical and seasonal distribution of various parasites - the bioclimatograph.

Not, however, until the work of Ollerenshaw and Rowlands (1959) on fascioliasis (liver fluke disease) was the potential of climatic factors as disease predictors fully realized. Since then, Ollerenshaw and Smith (1969), Ross (1970), Gettinby et al. (1974), Vlassof (1975), Starr and Thomas (1980), Gettinby and Paton (1981), Gardiner (1983) and others have made extensive use of climatic factors to predict the prevalence of several parasitic diseases of domestic ruminants.

Any forecasting system must be able to predict disease incidence on a suitable scale with acceptable success and be available early enough to be useful; current techniques are detailed in Appendix E. Briefly, the climatic forecasting system based on indices meets such requirements, but disease incidence is recorded on a non-physical, arbitrary scale. Development-rate models are explanatory and require a careful compilation of information on the dynamics of the parasitic life cycle - disease levels are accordingly represented in a form measurable in field experiments. Their flexibility makes them attractive but the level of detail required means that any parameters have to be correctly estimated if predictions are to be accurate. Often they are invaluable in identifying both those areas where experimental evidence is deficient or in need of revision and the most efficient and timely methods of control (Thomas, 1982).

Both methods imply a ready relationship between the conventionally measured meteorological factors and the microclimatic conditions within the herbage mat where much of the free-living stage of the parasites' life cycle occurs. Developments in modelling the host/parasite/environment complex will increasingly involve the meteorologist and the mathematician. Morley and Donald (1980), however, point to the small extent to which control procedures have been tested in realistic production systems and to the cost and difficulty of doing this. It is well to remember the comment by Michel (1982) that disease forecasts should be seen as aids to and not substitutes for good management.

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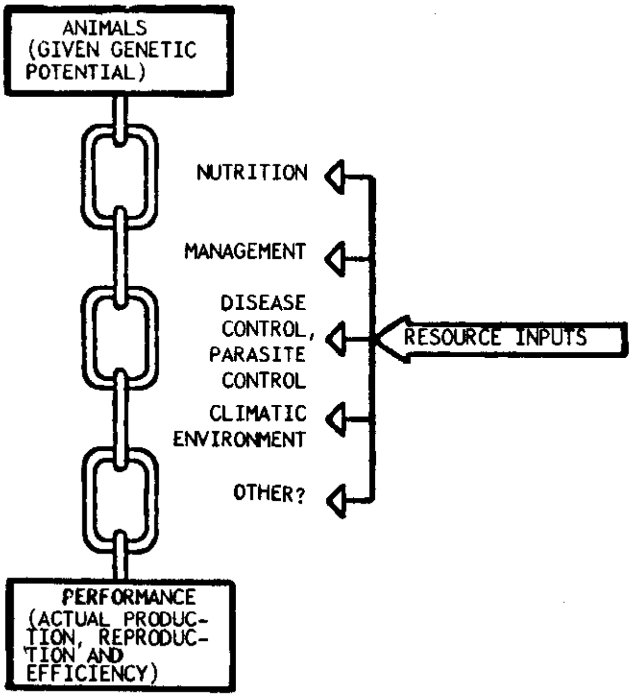


Figure 1.1 - Links in livestock production system (Hahn, 1981)

Physical environment (P, T, H, R, W, L) ± Disease and Parasites

± Feed and Forage ± Management ± Genetic potential

= Level of:
milk
or
egg production,
reproductive
efficiency,
growth

Figure 1.2 - Environmental factors influencing physiology and performance of livestock: P = precipitation; T = temperature; H = relative humidty; R = radiation; W = wind; L = light photoperiod (from Johnson, 1982)

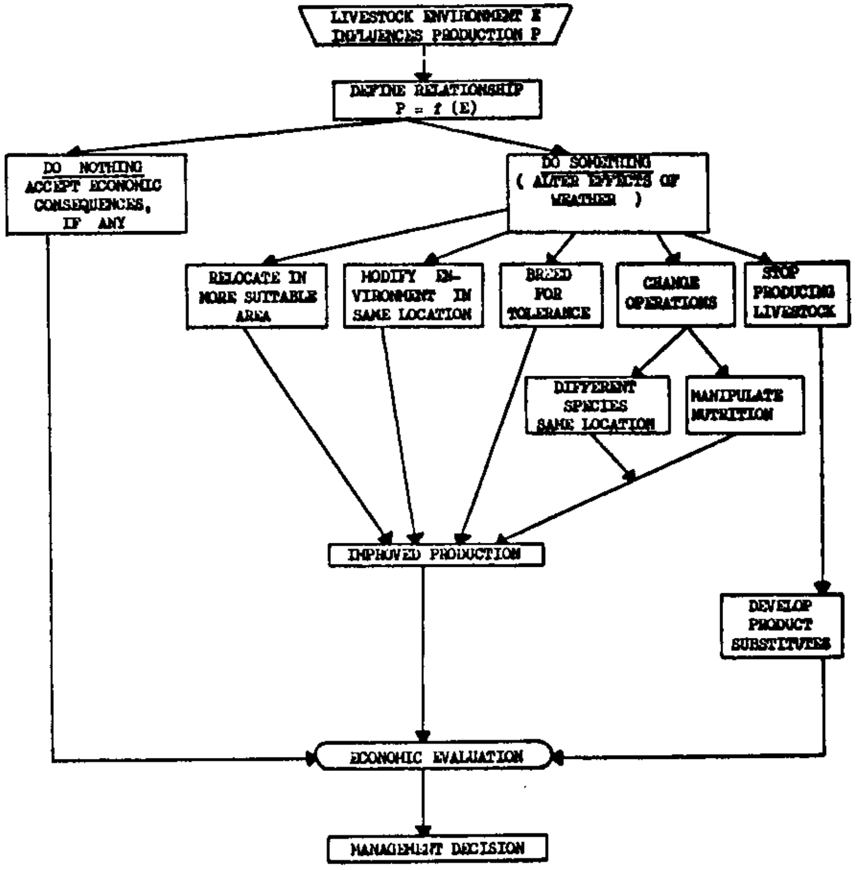


Figure 1.3 - Branching pattern of factors leading from environmentally induced production events to a management decision. Energy, social or other criteria can be substituted for the economic criterion in the evaluation stage (Hahn, 1982)

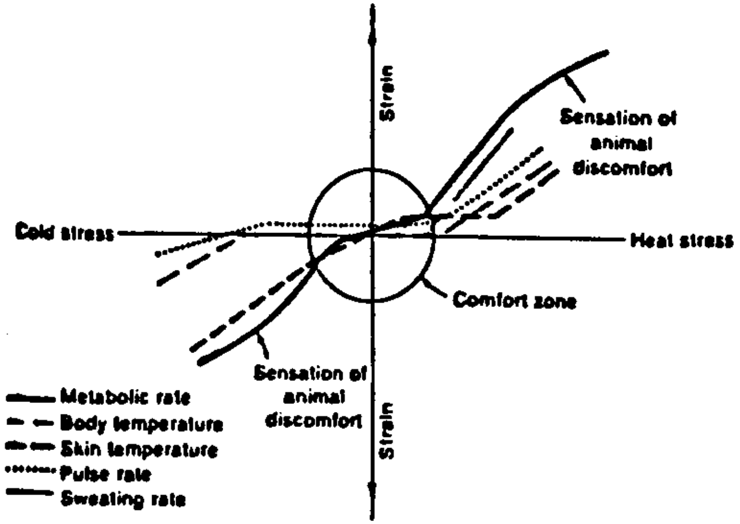
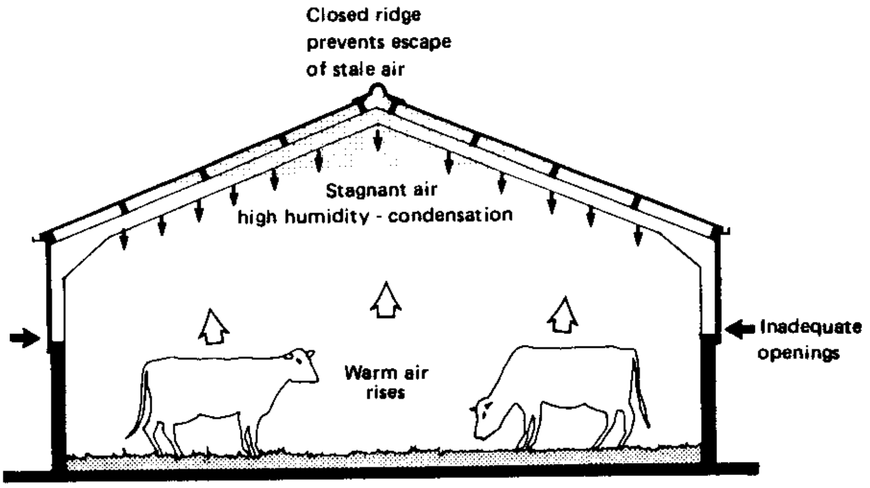
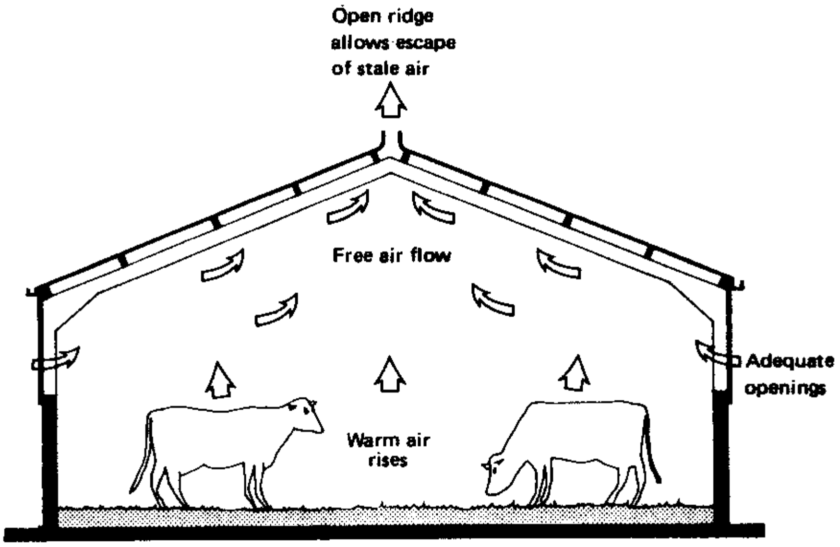


Figure 1.4 - Stress-strain relationships with progressive changes from low to high temperatures. The "comfort zone" represents the portion of the temperature scale where no consistent change in physiological processes can usually be measured. As temperature is increased or decreased, the stress is reflected by greater strain on the animal (McDowell, 1972)



(a) Poor design.



(b) Good design.

Figure 1.5 - Examples of "climate housing" for cattle in the United Kingdom of (a) poor design and (b) good design

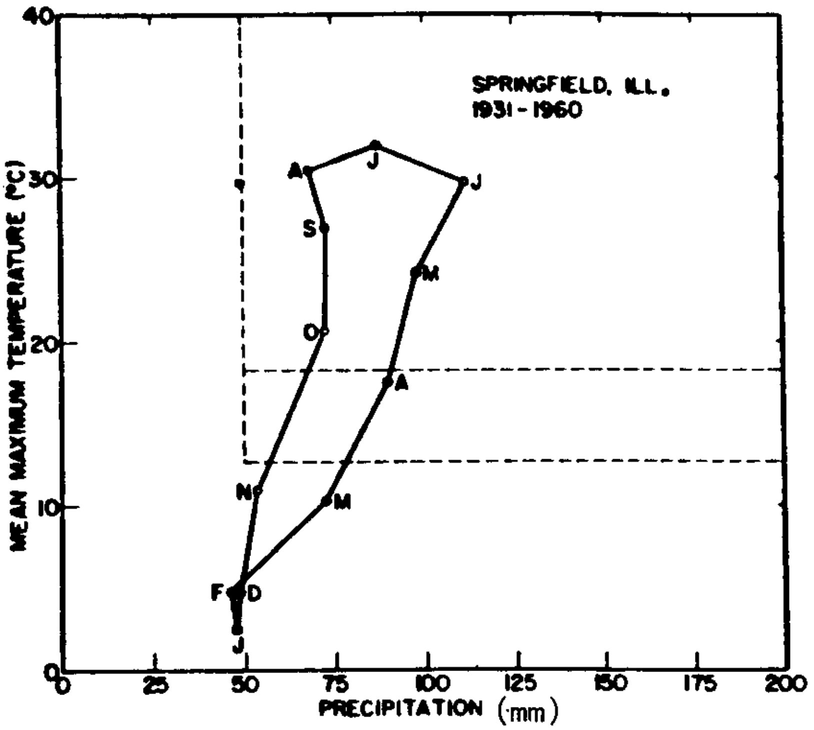


Figure 1.6 – Bioclimatograph of monthly mean maximum temperature against total monthly precipitation for Springfield, Illinois, USA (a _Haemonchus_ area), 1931-1960. The dashed lines are the limits indicating optimum conditions for pasture transmission of _Haemonchus_ (above) and _Trichostrongyhus_ (below) (_Levine, in Gibson, 1978_)

TABLE 1.1

Ambient temperature ranges and housing systems suitable for housed livestock (Sainsbury, 1981)

Type of animal	Ambient temperature range	Housing system
Adult milking cattle	Milk production optimum 10-15°C but little effect on yield from -7 to +21°C	Climatic housing usual and generally satisfactory
Beef cattle (from 3 months of age	-7 to +15°C the optimum range	Climatic housing appropriate but thermal insulation may be needed if bedding is absent
Calves	10-15°C at birth, which may fall gradually thereafter. Higher temperatures (15-21°C) are used in veal houses	Controlled-environment housing or kennels required
Lambs	4-21°C	Controlled environment may be used if housing intensive, otherwise kennels satisfactory
Adult sheep	-7 to +30°C	Climatic or kennels
Adult pigs	4-30°C	Climatic housing suitable where bedding is used but not with individually housed adults without bedding when minimum temperature should be at least 10°C higher
Fattening pigs	15-27°C	Controlled environment or kennel housing required
Young piglets	21-27°C	Artificial heating needed to supplement controlled environment
Brooding poultry	30-35°C	Artificial heating essential in controlled-environment housing
Broiler chickens	15-30°C	Artificial heating essential in controlled-environment housing
Laying poultry	15-21°C	Controlled-environment housing required with high-standard insulation or occasionally climatic housing with deep straw or other litter

TABLE 1.2

Examples of ventilation design for "climatic housing" of cattle

CALVES

All these environmental requirements need to be satisfied at the same time:

Volume of air space per calf for natural ventilation	Minimum 6 m^3
Inlet area per calf	Minimum 0.05 m^2
Outlet area per calf	Minimum 0.04 m^2
Height between inlet and outlet	Minimum 1.5 m
Air movement at calf level	Maximum 0.25 $m\ s^{-1}$
Relative humidity	Similar to external levels
Temperature	Similar to external levels except possibly for very young calves

ADULT CATTLE

Ventilation requirements	Area of inlet and outlet openings depend on: 1. Liveweight and number of stock. 2. Floor area of the building. 3. Difference in height between inlet and outlet.
Relative humidity	Similar to external levels
Temperature	Similar to external levels

TABLE 1.3

Some animal viruses which may be transmitted by the airborne route (Falk and Hunt, 1980)

Avian encephalomyelitis
Avian leukosis
Aleutian disease of mink
Canine distemper
Canine herpesvirus
Eastern equine encephalomyelitis
Equine infectious arleritis
Equine influenza
Equine rhinopneumonitis
Feline rhinotracheitis
Feline pneumonitis
Foot-and-mouth disease
Fowlplaque
Hog cholera
Infectious bovine rhinotracheitis
Infectious bronchitis of fowls
Infectious larygotracheitis of fowls
Infectious porcine encephalomyelitis
Marek's disease
Newcastle disease
Porcine enterovirus
Poxviruses
Rabies
Swine influenza
Transmissible gastroenteritis of swine
Wester equine encephalomyelitis

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TABLE 1.4

The impact of the weather on infectious diseases in animals

(Webster, 1981)

A. Biometeorological stimuli

"Thermic stimuli": air temperature, wind, rain, UV radiation

"Non-thermic stimuli": humidity, barometric pressure, ionization, pollution

"Change"

B. Biometeorological effects

Effects on the parasite

Direct: survival and spread of organisms

Indirect: survival and spread of intermediate host, distribution of final host

Effects on the host resistance

Direct: local resistance to infection at body surfaces, local clearance of infected organisms, systemic resistance to infection

Indirect: environmental damage at body surfaces, alterations to nutrition and behaviour, alterations to management

C. Analysis of effects

Correlation: statistical, empirical analysis of clinical records

Causation: experimental, biological investigation of specific effects of isolated stimuli on host and parasite

TABLE 1.5

Some recent estimates of the regional or national prevalence of fascioliasis (from Wilson et al. in Anderson, 1982)

Country/region	Prevalence (%)	Year
The Americas		
Brazil	2.85	1971
Chile	13.00	–
Cuba	3.8 – 43.0	1976
Mexico	73.90	1976
Uruguay	50.00	1977
USA		
Oregon	44.90	1976
Puerto Rico	31.76	1978
Texas	77.00	1972
Europe		
Belgium	20.60	1971
Denmark	8.0 – 19.0	1973
Finland	26.00	1969
Germany, Federal Republic of	11.80	1979
Italy	20.50	1974
	67.00	1975
	30.20	1973
Sardinia	27.0 – 48.0	1972
Poland	25.0 – 69.0	1973
Portugal	up to 60.00	1971
Switzerland	11.5 – 23.0	1975
	54.00	1977
United Kingdom	5.63	1980
USSR	65.00	1977
	37.60	1975
Yugoslavia	34.9 – 62.8	1977
Australasia and Asia		
Australia	13.0 – 30.0	1977
China	10.17	1976
Indonesia		
West Timor	12.00	1979
West Sumatra	86.00	1979
New Zealand	6.00	1972
Taiwan	30.90	1976

TABLE 1.6

Relationship of climate to ruminant nematodes

(from Levine, in Gibson, 1978)

Climate	Typical locality	Dominant trichostrongylid
A Tropical: rain, hot all year	Equatorial Africa/ America	*Haemonchus*
B Dry steppe: (> 18°C)	Texas	*Haemonchus*
(< 18°C)	Idaho	*Ostertagia*
C Temperate: -3°C to 18°C		
moist all year, hot summer	Washington, DC	*Haemonchus*
moist all year, warm summer	England, Germany	*Ostertagia*
D Cold: below -3°C to above 10°C	Canada	*Trichostrongylus*
E Polar: below 10°C	Arctic	None

CHAPTER 2

PROPOSALS AND EXAMPLES FOR INCLUSION IN CURRICULA OF MULTIDISCIPLINARY TRAINING PROGRAMMES

2.1 Education and training

To tackle problems in animal health, the meteorologist must add an understanding of current farm practice (WMO, 1988) to his knowledge of meso- and micrometeorology. In addition, he will need to be aware of the implications of ambient conditions for animal husbandry, pests and diseases, for vegetation and soils and for environments within farm buildings. Generally, this will mean self-education with considerable self-motivation; a training course can at best indicate the way ahead. Useful results and application will only follow if meteorologists ask questions of livestock specialists and then apply their own physical understanding of animal-environmental interactions to provide guidelines for operational measures. For the livestock specialist there is a corresponding requirement to comprehend certain micrometeorological interactions and, particularly, the limitations to standard measurements when attempting to apply them, for example, "in house" or within the herbage mat.

2.2 Examples

Chapter 1 introduced the effects of climate and weather on animal production. The appendixes present examples and case-studies of the role of weather-based decisions in livestock management and economics and are, thus, a source of strategic and tactical techniques and of research and development suggestions. Discussions of the examples and case-studies indicate short-comings in the operational techniques and areas where improved meteorological inputs and/or a better understanding of animal health and productivity and meteorological factors are needed.

The following is a list of techniques particularly appropriate for inclusion in the curricula of training programmes in agricultural meteorology together with suggestions for further studies which should be stimulated by such interdisciplinary courses. Participants should be encouraged to bring for analysis the meteorological data relevant to their own region.

2.2.1 Management perspectives (Chapter 1 (section 1.1), Appendix A and sections of Appendix C)

(a) Establish relationships between some aspects of an animal's physiology and meteorological factors (e.g. Figure A.1, Tables A.1 and A.3), using data supplied by veterinarians;

Could the response indicate a requirement for environmental modification or a different genotype? (Veterinary advice is needed here.);

(b) Rational decision-making: Given the cost of a range of housing and feeding alternatives appropriate to your region, does a sample decade of weather factors bear out the current husbandry? (Table C.4);

(c) Choose an appropriate index for some class of livestock and map an environmental profile for your region (e.g. THI index or degree-days above or below a given base). Use data such as in Table A.4 to convert to production decline (Figures A.7, A.8 and C.2);

(d) Estimate expected summer season (122 days) milk-production loss for cows normally producing 22.7 kg (50 lb) per day (NL). Use the following table which is derived from Figure A.7 (Hahn and McQuigg, 1970):

Expected number of days per 122-day season in each THI interval (based on 20-year climatological record)

THI Class interval	Expected no. of days in interval
69.6 to 70.5	9.0
70.6 to 71.5	9.9
71.6 to 72.5	9.6
72.6 to 73.5	10.2
73.6 to 74.5	9.0
74.6 to 75.5	9.3
75.6 to 76.5	6.4
76.6 to 77.5	6.9
77.5 to 78.5	4.2
78,6 to 79.5	2.2
79.6 to 80.5	0.6
80.6 to 81.5	0.0
81.6 to 82.5	0.1

Hints (from Table A.4):

Production loss $P.L = -1.075 - 1.736\,(NL) + 0.02474 \times (NL) \times (THI)$ kg

$$\text{Seasonal} = \sum_{THI = 70}^{82} D(P.L)$$

THI	D	P.L	D(P.L)
<73	–	no loss	–
73	10.2	0.54	5.52
74	9.0	1.10	9.90
.			
.			
.			
.			
82	0.1	5.6	0.56

$\sum D(P.L) = 89$ kg

(e) Using any available productivity-shelter information, study the costs, benefits and disadvantages of establishing various natural or artificial shelterbelts;

(f) If animal housing is available for practical work, use a "smoke puffer" to observe air circulation within various forms of housing under contrasting meteorological conditions and by day and night. If possible, quantify measurements with a hot wire anemometer or sensitive cup counter. Note particularly air flow near stock and evidence of air stagnation. Take temperatures and relative humidity measurements. If at all possible, use gas concentration measuring devices to estimate air change rates (Smith, 1972):

Do data suggest housing is appropriate, well designed? What modifications might improve air flow and air quality (e.g. "opening up" roof holes to improve natural ventilation, rearrangement of stalls or ventilation entrances and exits, use of cooling systems, better roof or wall insulation)?

2.2.1.1 Siting

(a) On site - look for housing on a variety of sites (e.g. on top of hills, in hollows, surrounded by other buildings or trees). Can incidence of respiratory disease be related to these categories of siting? If possible, establish daily meteorological readings (temperature and wind speed);

(b) Data analysis: does disease incidence relate to particular meteorological data (e.g. low wind speed), allowance being made for the incubation period of the virus? (See also 2.2.4 (c).);

(c) Study possible connections between a local viral respiratory disease and factors such as (a) sharp temperature changes, day to night (say 1.5 times monthly average value); (b) two such sharp changes within the incubation period of the virus (see Smith *et al.*, 1972).

2.2.2 Housing for animal production (Appendix B)

(a) Relate findings 2.2.1 (b) and (d) above, to the benefit-cost of some form of housing or shelter;

(b) Establish design temperatures (t_5, t_{10} ... t_{90}, t_{95}) for your chosen region (Tables B.2 and B.3).

2.2.3 Stress (Appendix C)

(a) Discuss with interdisciplinary teams, including extension service, the lines of communication, promotional activities, etc., needed to establish operational forecasting of some stress factor (heat or cold);

(b) Plot the progress of a summer or a winter period using, for example, departure of temperature and rainfall from average (Figure C.7) and relate it to some stress-connected health problem, e.g. severity of pregnancy toxaemia, botulism, etc. How did the seasonal disease rating relate to prediction after one month, two months ....?;

(c) Devise a "drought index" e.g. number of dry days per month, potential soil moisture deficit, etc. (Figure C.5). Examine the geographical variation of this index and, using rainfall data, estimate probability of achieving a given amount of rainfall in the next month so as to mitigate drought effects;

(d) Draw maps of "day degrees" above or below a base temperature representative of an upper or lower critical temperature for a class of livestock fed at maintenance (see 2.2.1(c)).

2.2.4 Airborne infection (Chapter 1.4 and Appendix D)

(a) Deduce "red sectors" for most likely infection areas for data tabulated in Figure 2.1 (follow methodology of Figure D.2);

(b) Draw potential infection sectors for a short period of your own hourly data and preferably for a period preceding the outbreak of an airborne virus disease in your area;

Are there indications that secondary outbreaks could have been due to airborne spread?;

(c) See 2.2.1.1(c).

2.2.5 Parasitism (Chapter 1.5, Appendix E and Appendix C, section 1.4)

(a) Plot a "bioclimatograph" (Figure 1.6) for your area and note its implication for the seasonal occurrence of various classes of parasites for which threshold temperatures for development are known;

(b) Following Figure C.7, monitor the seasonal progression of weather and predict likely intensity of a locally important disease after a few months. Did the forecast bear out the actual incidence?;

(c) Development fractions

The development of parasite eggs to a larval stage was studied in a constant temperature chamber:

Temperature $\bar{T}$°C	Development time (days)
5	Did not develop
10	10
20	3 1/3
30	2

How many days will development take in the field under the following conditions?

Day	Maximum temperature T_x°C	Minimum temperature T_N°C
1	15	5
2	20	2
3	25	10
4	30	15
5	20	0
6	14	4
7	26	13
8	17	11
9	:	:
:	:	:

Hint: find relationship D = f(T) by plotting $\frac{1}{D}$ v $\bar{T}$

(Base temperature T_r = 5°C)

Using $a = \frac{T_x - T_r}{T_x - T_r}$ and $\bar{T} = \frac{T_x + T_r}{2}$ when $T_N < T_r$

find day n for which $\sum_n \frac{a_n}{f_n(T)} \geq 1$

Answer: $D = \frac{10}{(0.2T-1)}$

$\sum \frac{a_n}{D_n}$ (= 0.10 + 0.125 + 0.25 +0.35 + 0.11 + 0.08 + ...)

for n = 6.

2.2.6 Operational disease warnings - methodology (Chapter 3)

(a) Discuss possible strategic and tactical health warning - management aid systems - appropriate to your area. What data are available for case-studies of past events (in order to arrive at the basis for operational advice)? Involve extension service colleagues if possible and investigate possibilities of an operational programme.

- What data bases must be developed?
- What communications are necessary?
- What is the lead time? Is the warning timely?
- Is further development of this operational technique likely to be cost-effective?;

(b) Identify problems in producing an operational warning system. Are they due to:

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- Lack of agrometeorological skills?
- Lack of a meteorological data base?
- Lack of a biological data base?
- Lack of interest by extension service?
- Poor communications network?
- Other?

What can the agrometeorologist and/or the meteorological service do to influence the shortcomings? Could you identify user-response if an operational programme is launched?

2.3 Overcoming shortcomings in methodology and data

It will be clear that the examples may not be immediately appropriate to, or bear translation to, another climate. However, the techniques developed suitably modified will often be applicable elsewhere and for similar health problems.

Biological data may be lacking for the country or species concerned: meteorological/health interactions may either be ill-defined or completely absent. There may be gaps in knowledge which will suggest both opportunities for further interdisciplinary work and the type of further information required from livestock research institutes and meteorological departments. International organizations (e.g. FAO) may well have vital data.

2.4 Relationship with crop husbandry specialists

As discussed in Appendix C, section 2, one of the indirect effects of weather stress for livestock is the influence on the quality of pasture and forage.

Meteorologists with crop specialisms and crop husbandry specialists working as part of the agrometeorological team are in a position, therefore, to make important inputs into studies of animal productivity.

(a) How does climate limit pasture production or the grazing season in your area? Are temperature or rainfall limiting or some other factor (e.g. soil fertility, drainage)?;

(b) Study an arid-zone range management system in the light of the key factors (a) and (b) noted in Appendix C, section 2.1. What is the challenge of disease (e.g. parasitism)? Is management capable of taking advantage of suggested programmes?;

(c) Study techniques of hill pasture improvement. Is sufficient attention paid to meteorological inputs?;

(d) Discuss the importance and possibility of weather-based operational predictions of pasture quality (e.g. "D" values) for the local livestock classes;

(e) Using past data, establish frequency of runs of 1,2,3, ... dry-days which might indicate potential for silage or hay (N.B.: a "dry-day" is not necessarily a "drying-day" (see Appendix C, section 2.4).

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2.5 Summary

WMO and national training programmes should seek to include more livestock meteorology in curricula alongside crop and water-balance studies. Not only are such studies likely to pay handsomely economically; livestock are an essential link in the agricultural cycle, and this should be reflected in the structure of training courses. The design of the necessary data bases and lines of communication with extension services to implement these operational techniques should be discussed. Here, the agricultural meteorologist may need to make policy recommendations both to the national Meteorological Service and to the extension services (WMO, 1983).

* * *

SURFACE WIND DIRECTION																																				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	Calm
///														/			///											//	//	////	////	//	//// ////		/	//// //// ////
3														1			4											2	2	5	5	2	9		1	15

ADVICE GIVEN: Outbreak at: TQ 248 125:-

PERIOD COVERED	22.1500 to24.1500 GMT
RED SECTORS	100° to 230° through south; commonest direction 160° - 9 hours, 15 calms 320° to 040° through north; commonest direction 360° - 4 hours.

Figure 2.1 - Information received concerning 36-48 hours' old outbreak (hypothetical) on 24 June 1969 at 15h00 and grid reference TQ 248 125 (six miles NW of Brighton, Sussex, England)

C H A P T E R 3

GUIDELINES FOR OPERATIONAL PROGRAMMES TO BE ADOPTED BY EXTENSION SERVICES

3.1 Aim of operational forecasts

In discussing the aims and objectives of animal health and disease forecasting, Hugh-Jones and Yvoré (in preparation) note that the priority aim is for advice which is accurate, reliable, timely and appropriate to health problems of undoubted economic importance which will be improved by action. (Accuracy may be in terms relative to previous events; the use of numbers can imply a misplaced precision.) It should be remembered that, generally, the management or husbandry implications of the forecast will be for extension or advisory services of an agriculture department to interpret and to recommend action. Action must be timely - sometimes the time of action is short as in temperature/stress-related problems; epidemiological teams can react to meteorological advice on foot-and-mouth disease spread on an hour-by-hour basis. Other health problems such as fascioliasis have a lead time of several months.

3.2 Priorities

The economic importance of the health problem to productivity must be considered and the disease should be capable of response to management action. Forecasts of the possible changes in quality and quantity of animal products coming onto the market are of considerable advantage to economic and management services within national agriculture departments. Most, if not all, livestock health problems will respond to increased management inputs. However, priority in offering weather-based advice, given limited agrometeorological resources, should be given to those conditions yielding the highest economic returns on prevention or cure (CAgM, 1984).

3.3 Uses of weather-based inputs for animal production

(a) Strategic: planning and direction of health programmes including building and shelter design;

(b) Tactical: timely warnings optimize awareness of regions at risk allowing economic use of manpower and treatments.

Advisory or extension services should be made aware of the "advisory" value of the meteorologists. As a member of an interdisciplinary team, the meteorologist's input "on site" to the planning, siting and daily running of an enterprise can prove invaluable (see Appendix B, section 3). Day-by-day requests for advice on animal housing problems and associated health risks should - perhaps must - involve the meteorologist. With farm building specialists, the meteorologist can make a powerful contribution to studying airflow and ventilation characteristics; with microbiologists and veterinarians, the question of air hygiene can be studied on site (see Appendix B, section 2.1). The attachment of a meteorologist to the advisory arm of an agriculture department is ideal. Surrounded by experts of other disciplines, he is able to input both strategic plans and be a member of an "on-site" advisory team (NAS, 1976);

(c) Supportive: farmers are not entirely helpless victims of the weather. Specific warnings with advice on preventive measures may create positive attitudes to the environmental and agrometeorological services;

(d) Research: collaborative studies have proved their worth and have frequently demonstrated areas where vital knowledge required for disease control is lacking. Techniques can often be translated to new problems or different countries.

3.4 Data bases

There is a requirement for an agrometeorological data base for key meteorological parameters for hourly and daily stations and for areas. Facilities should be developed so that this basic information can be manipulated to give derived parameters: e.g. "day-degrees" above a given base, potential evapotranspiration, soil moisture deficits, frequencies of occurrence of rainfall quantities, temperatures and wind speeds. With meteorological services will also rest the requirement for quality control of these data and for responding to extension service requests for additional routine measurements such as soil temperature and pasture canopy wetness (WMO, 1987). Additionally, certain key developments in information technology such as radar-measured rainfall and satellite estimates of surface fields of meteorological parameters are likely to contribute immensely to the agrometeorology data base.

By contrast, the data on animal health and disease are often sparse and/or subjective and qualitative in space and time. For various reasons, farmers and private sector veterinarians may not be prepared to release animal disease information and the main source will often be the abattoir or public sector veterinary service. Yet such a data base would pay dividends, particularly if health statistics were denoted quantitively and identified by date of occurrence.

3.5 Problems of weather-based inputs

(a) Mistakes will occur since weather/animal health relationships can never be totally defined and management requirements can dominate in otherwise adverse situations;

(b) Costs of supporting agrometeorological research teams and the assorted infrastructure teams may be comparatively inexpensive but they still have to be met, often as government-funded agencies. However, success will prove highly beneficial and agrometeorological teams must ensure that the value of their input is understood by the extension service and associated agriculture department;

(c) "Probability" inputs can be misunderstood; they also imply that future years will produce a similar frequency distribution and combinations of meteorological events as has the data-base period.

3.6 Guidelines for extension services

(a) Agrometeorological teams have a number of systems to aid extension services in giving operational advice on various weather-sensitive aspects of animal health and production. Many WMO publications deal with experimental, operational and economic aspects of animal health studies (WMO 1970(a) and (b); 1972; 1978; 1980(a) and (b); and 1981). Such techniques can often be used in whole or in part and adapted to diseases and areas other than those for which they were developed;

(b) It is essential to start with an interdisciplinary team and a disease of undoubted economic importance for which a meteorological input has had proven success elsewhere;

(c) At the same time, an adequate meteorological and disease data base is required or must be established if techniques are to be extended to a new region.

Once the potential operational measure has been established as appropriate to the region, several years of trials are clearly advisable, using local and/or regional data. At all times, liaison between extension, meteorological and other disciplines will permit limitations of the measures – whether due to data or modelling – to be understood. During this period, discussions will be held on the most rapid and effective methods of promoting the operational measure to farmers as well as on the appropriate timely countermeasures to be adopted.

Trials with a limited number of volunteer farmers should be considered and their feedback noted, both as to how their management was able to respond in the "lead time" available and, where applicable, suggestions as to a likely costing of the service. Here national Meteorological Services must obviously be involved so that, for example, the tactical supply of data and forecasts can be realistically costed. Some services supplied will be produced routinely by weather centres, others will require a special input.

3.7 Communications, promotion

In promoting the operational scheme, advertising would be necessary in agricultural bulletins and other publications, farmer-dedicated radio and television services (e.g. Prestel in the United Kingdom; Green Thumb Box in the USA) and through farmers' organizations. Displays of the cost-effectiveness (and limitations) of the service at agricultural shows and demonstrations are also a powerful promotional approach. More specifically, the publishing of results of the development of an operational technique should not be restricted to the more esoteric scientific literature. Bulletins prepared by the agrometeorologists and their veterinary colleagues could be made available regularly in circulars and advisory service publications to draw attention to the value to the agricultural industry of meteorological inputs. An indication of the shortcomings of the weather inputs and their implications for management should be clearly stated.

3.8 Summary

Maunder (1977) notes that of prime importance is the continuing need to assess and present weather inputs in terms of production figures, costs or similar measures which can be used directly by decision-makers.

Highly mechanized and intensive livestock production is extremely sensitive to the weather and sophisticated meteorological advice is required. At the other extreme, farming in many countries would benefit from even a very basic level of advice based on weather inputs and strategic and tactical planning of livestock production (CAgM, 1984). It is the meteorologists' responsibility to seek out the most useful health problems, in terms of economics and available biological information, so that interdisciplinary teams can see through to a conclusion the necessary additional research, development and promotion, and establish an operational role for meteorological inputs (Rijks, 1984).

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APPENDIX A

MANAGEMENT PERSPECTIVES

A.1 Measuring animal performance

It is the increased understanding of the response of animals - in terms of feed intake, reproduction and adaptation - to their meteorological environment that has, according to Duckham (1967), contributed to the marked reduction of variability of farm output since the 1920s in technologically advanced countries.

Johnson (1982) gives many examples of the response of growth, reproduction, lactation and other physiological responses in cattle to meteorological factors (Tables A.1, A.2, A.3 and Figure A.1). Such knowledge of livestock responses to the thermal environment has led to development of functional relationships for feed intake, growth in milk and egg production, and conception rates for specific species, breeds and life stages. Examples of currently available relationships ("responses") between meteorological factors and the performance of dairy cows and poultry are given in Table A.4.

To be definitive, such relationships should include the full range of meteorological parameters. However, attempts to characterize these influences of the thermal environment using measurements other than air temperature, humidity or wind speed have not generally been satisfactory. This is probably due to:

(a) The animals' ability to compensate for short-term thermal stress;

(b) Variation among species in the energy-conserving or dissipating response;

(c) Large standard errors due to individual and breed differences.

From biological and managerial standpoints, compensatory performance, noted in (a), is a means of working within the animal's capability of adaptation; from an engineering viewpoint it is a means of widening the relatively narrow control band sometimes advocated for thermal conditions in livestock housing. Studies on this capability will now be mentioned.

A.1.1 Compensatory capabilities

Von Bartalanffy (1968) and Hahn (1982(a)) describe various series of experiments on growing livestock showing that stock fed *ad libitum* have considerable ability to recover from depressed growth during moderate heat stress through compensatory gains in non-stress periods - the "principle of equifinality" (Figures A.2 and A.3(a) and (b). The compensatory capabilities (resilience) of livestock means that short-term stresses may be less significant in terms of maintaining the productive function (Hahn 1982(b)). However, there are not sufficient data to incorporate such thermal criteria in a guide to rational managerial decisions (this is especially true for cold climates), although indices which could monitor the accommodation and

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dissipation of thermal stress have been proposed as a tactical guide to counter stress by Christianson et al. (1982) - initially for finishing hogs.

There is, therefore, a need for research into definitions of the mechanisms involved and of the threshold limits and stress duration before meteorological interpretation can be used to provide a basis for rational selection for livestock environments.

A.2 Characterizing the environment

Apart from these adaptive and behavioural capabilities of the animal, there are other problems in characterizing the environment associated with limitations of physical measurments (Hahn 1983), although there are several classifications appropriate to crop growth (e.g. Köppen and Geiger, 1936; Duckham and Masefield, 1970) and many indices have been developed to characterize the thermal comfort of humans as summarized by Kerslake (1972) and Cena and Clark (1981).

Ideally, sensors or indices should combine, for example, a measure of the relative heating or cooling power of the environment. The object is to achieve some readily comprehensible index for comparing livestock environments and to present, in a single variable, factors that characterize both the thermal environment and the stress it imposes on particular classes of livestock. This search has led physiologists in two directions - empirical indices have been derived from laboratory and field experiments and instruments have been developed to simulate heat loss. Monteith (1974) has proposed that the heat balance approach can incorporate all the experimental and physiological variables and is a strong candidate for the basis of a climatological index. The extensive list of indices has been reviewed by Smith (1970), Kerslake (1972), Mather (1974), Mount (1979) and Starr (1981). Hahn (1981), however, notes that a proliferation of climatic indices characterizing an environment is to be avoided - the cost and logistics of applying many indices would far outweigh benefits. In practice, therefore:

- No sensor measurement or index represents a single, widely accepted and, hence, routinely measured parameter;
- Sensor locations do not generally represent the animals' microclimate;
- Considerable commitment of manpower and facilities is needed.

Nevertheless, some successes in surveying the agroclimatic environment have been reported.

A.2.1 Agroclimatic surveys

Agroclimatic surveys using suitable indices are discussed in the Guide to Agricultural Meteorological Practices (WMO, 1981) and by Mischenko (1984). Such surveys have assisted in developing climate summaries that have been used to improve livestock performance as reported, for example, by Bonsma and Joubert (1957) who developed climate summaries for South Africa, enabling livestock production to be established. McDowell (1967) quotes an example of the use of climate summaries in northern Columbia which provided the basis for the development of calf housing and parasite control that resulted in a substantial reduction in calf mortality. In this case, the optimum practices

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suggested by attention to climate data proved quite different from the traditional husbandry of the area. Indian studies are reported by Somanathan and Rajagopalan (1984).

A.3 Climatological information for strategic decisions in animal management

A lack of strategic planning means that, in adverse weather, management options are often quite limited. Hahn (1982(a)) gives a graphic example of livestock losses without planning for adequate shelter. More than 700 dairy cows died in a three-day period in 1977 in California, USA, when high humidity was aggravated by high temperature and radiation levels (Oliver et al., 1979). Adequate shade reduced death losses to 33 per cent and production losses of surviving cows to 5 per cent compared to those occurring without shade.

Probability analysis provides an objective way of expressing this uncertainty of climate in a given location, allowing a manager to select a risk level compatible with his estimate of value of alternatives. The method has been used successfully with swine (Morrison et al., 1970 (see Figure A.4 and Appendix C, section 1.1.1)), broiler growth (Hahn and Nienaber, 1976) and egg production in hot weather (Hahn, 1976) (see Figure A.5), in addition to milk production (Hahn and Osburn, 1970; Hahn and Nienaber, 1976) (Figure A.6).

Examples:

(a) To plan livestock shelters objectively, Hahn et al. (1970) studied a functional equation for the decline in milk production (see Table A.4):

$$M.DEC = -1.075 - 1.736NL + 0.02474\,(NL)(THI)$$

where: M.DEC = the actual decline in milk production (kg/cow/day);

NL = the normal production level (kg/day);

THI = the daily mean temperature-humidity index = $t_{db} + 0.036t_{dp} + 41.2$ (where t_{db} and t_{dp} are dry-bulb and dew-point temperatures, respectively (°C)).

Probability distributions of daily mean THI were obtained for 16 USA locations from 20 years of hourly climatological data for the summer season (1 June to 30 September), when milk production decline is normally greatest. Figure A.7 contains the distribution function, an ogive curve, for Columbia, Missouri, USA. As THI becomes larger its frequency is less but the decline in production is larger. Nomograms at the right-hand side of the figure permit values of production loss to be calculated for two levels of production: 22.68 and 45.36 per day. From this graph, the probability of production loss is also obtained, since THI and loss are related by the equation given above. For example, the probability that a cow producing 22.68 kg of milk on a certain day will suffer a loss of 0.91 kg is 0.32.

The distribution function and nomograms can also be used to evaluate the number of days of occurrence (out of 122 in the average "summer") for each integral value of THI when loss occurs. Integration of production declines over the entire period, performed by considering the THI intervals from 70 to 82 for each level of production, provides an estimate of expected summer season losses. (The procedure is given as an example to be worked in Chapter 2, section 2.1.)

$$\sum_{THI = 70}^{82} \text{(production decline)} \times \text{(no. of days in THI interval)}$$

Such calculations are useful for an economic analysis of the possible savings to be realized by constructing shelters to control the temperature and humidity of the cows' environment. Any resultant increase in production must be sufficient to cover the capital and operating costs of the shelters. In this case, predicted production losses were within 5 to 17 per cent of observed values. This agreement has established a reasonable link between the laboratory-derived functional relationships (the model) and the real world (the commercial system or prototype);

(b) Functional relationships can also be used to assess weather impacts in specific years. Hahn (1981) used the milk production decline response function (Table A.4) to estimate the effects of the extreme 1980 summer on dairy cow performance at several locations. The results indicated that high-producing, shaded cows in southern areas of the USA underwent severe production declines, but declines in northern areas (where the majority of cows are located) were near or slightly below normal (see Table A.5);

(c) Hahn and Osburn (1970) predicted the benefits of summertime evaporative cooling for dairy cows in the USA (Figure A.8). Despite limitations in the reduction of production losses, evaporative cooling appeared to have considerable economic potential (Hahn and Wiersma, 1972) while air conditioning of this housing to eliminate losses is scarcely feasible (Table A.6).

Selection among alternatives may also involve reassessment of design criteria. Thus Hahn et al. (1970) established criteria for the height of shades for livestock housing on the basis of cloud-cover probabilities. Housing "design temperatures" are discussed in Appendix B, section 1.2.

Consideration of animal production strategies should clearly include examination of animal/pasture management interactions e.g. the energy cost of travel to pasture, use of feedlots (zero grazing), rotation of pastures, feed conservation techniques, harvesting/marketing of the animals before weather-imposed seasonal declines in bodyweight become important, etc.

A.3.1 Tactical decision-making in animal management

The two types of weather information involved for tactical decision-making are forecasts and current weather descriptions; there is a need for weather information tailored to livestock purposes. Most livestock-orientated tactical decisions involve extensive or semi-intensive production systems. Intensive and totally confined production systems usually buffer livestock from external conditions although confinement can worsen the impact of specific weather events, particularly in hot weather (Appendix B). Hahn (1982(a)) gives examples of the level of vulnerability of livestock to weather stress during various stages of the life cycle involving tactical selection from alternative sources of action following a forecast. At parturition, for example, a forecast can guide tactical decisions on activating auxilary heat sources in cold weather or water sprays, fans or other cooling devices in hot weather.

In the USA, livestock weather safety statements are issued when the livestock weather safety index is in the danger or emergency category (Figure A.9). Livestock managers can then consider tactical actions such as postponing stressful activity or taking measures to limit stress (e.g. handling in early morning, wetting stock, minimizing exposure to solar radiation, etc.) (WMO, 1986).

Further examples are introduced as appropriate in Appendix C.

A.4 Livestock production and energy requirements

The economics of livestock production require studies of energy demands not only for heating and cooling buildings but also for the labour and fuel requirements of sowing, fertilizing, harvesting, processing, transporting and storing (Barth, 1982; De Shazer and Overshults, 1982). At each stage there is a role for meteorological inputs of both a strategic and tactical nature (Robertson, 1980).

The incorporation of meteorological information into longer-term investment decisions in assessing the economics of housing and evironmental control systems is discussed next in Appendix B.

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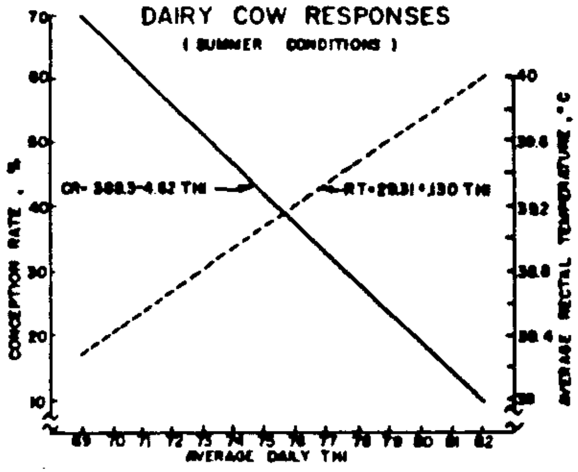

Figure A.1 - Response relationships for conception rates (CR) and rectal temperatures (RT) of dairy cows as a function of the temperature-humidity index (THI)*, based primarily on field observations in Mexico and Hawaii (adapted from Ingraham, 1974)

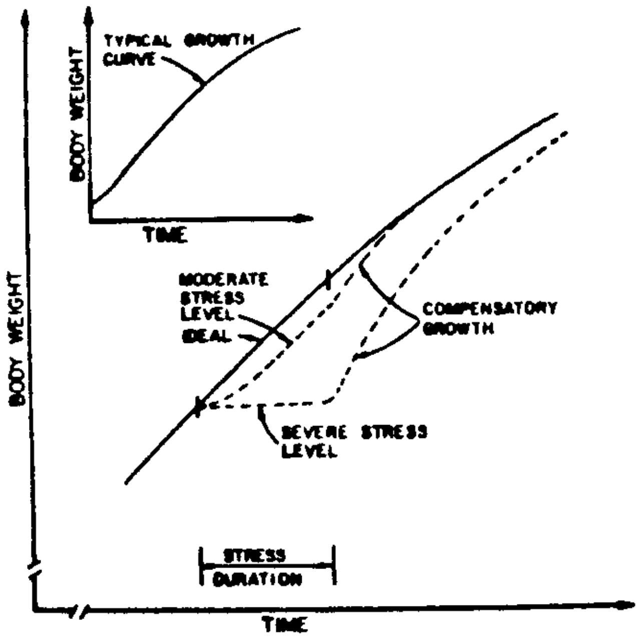

Figure A.2 - Schematic of the principle of equifinality (von Bertalanffy, 1968) as applied to growth of livestock subsequent to exposure to moderate and severe stressors (e.g. hot weather). For severe stress levels, full compensaton may not be achieved in an acceptable time period for marketing or breeding animals

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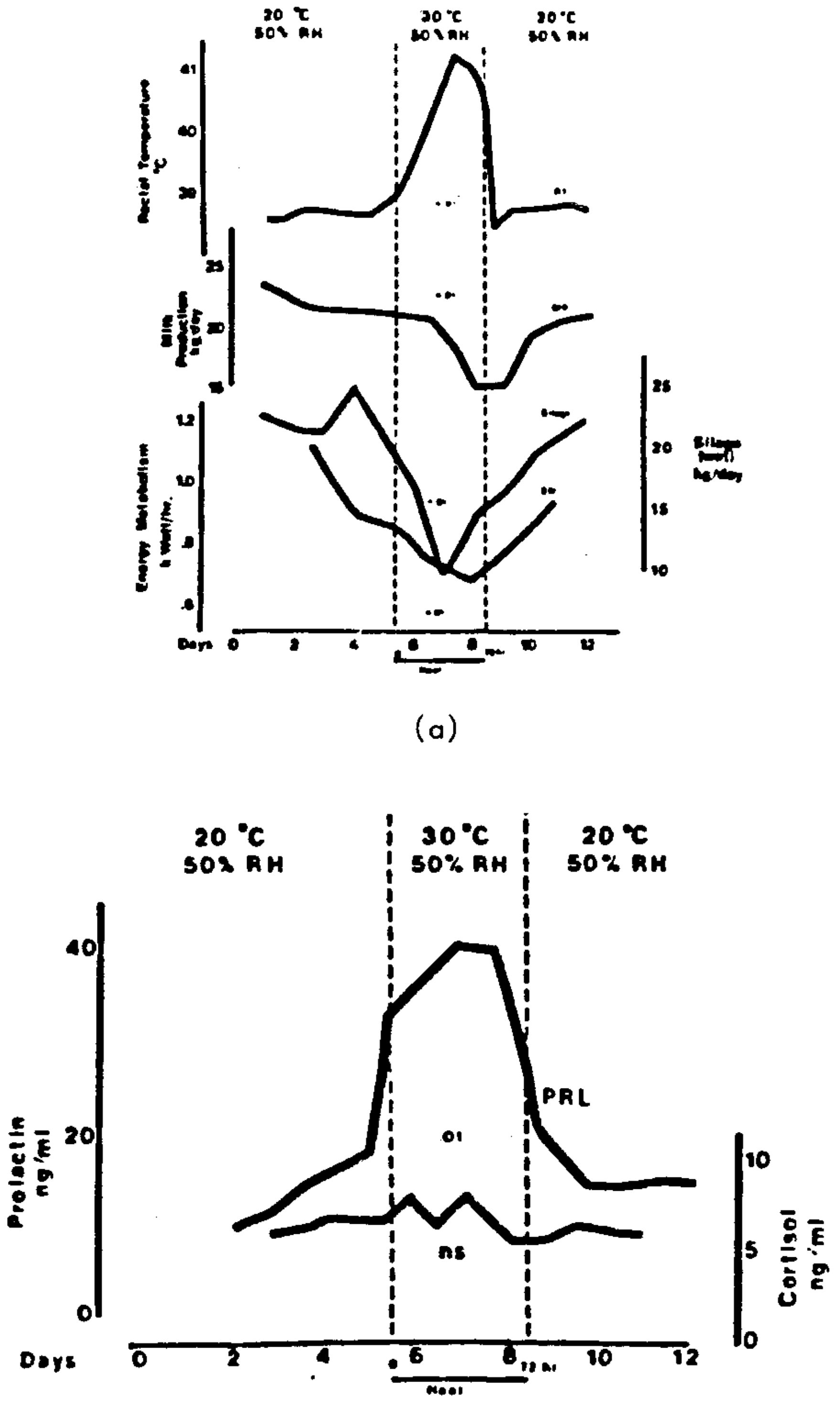
* THI is a derived statistic computed from the relation:

$$THI = t_{db} + 0.36\ t_{dp} + 41.2$$

where: t_{db} = dry-bulb temperature (°C);
t_{dp} = dew-point temperature (°C)



(a)

(b)

Figure A.3 - (a) Trend physiological and production data for a comprehensive compensatory study to relate physiological and performance changes; and (b) trends in physiological changes, prolactin and cortisol (Johnson, 1982)

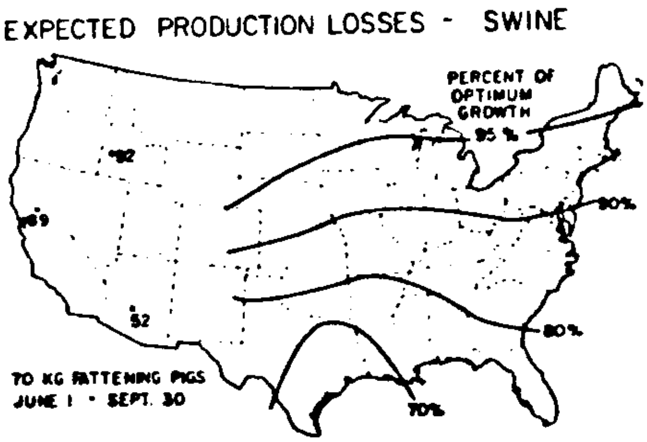


Figure A.4 - Expected production losses as percentages of optimum growth rates for shaded 70 kg finishing hogs subjected to natural summer weather (1 June - 30 September) (adapted from Morrison et al., 1970)

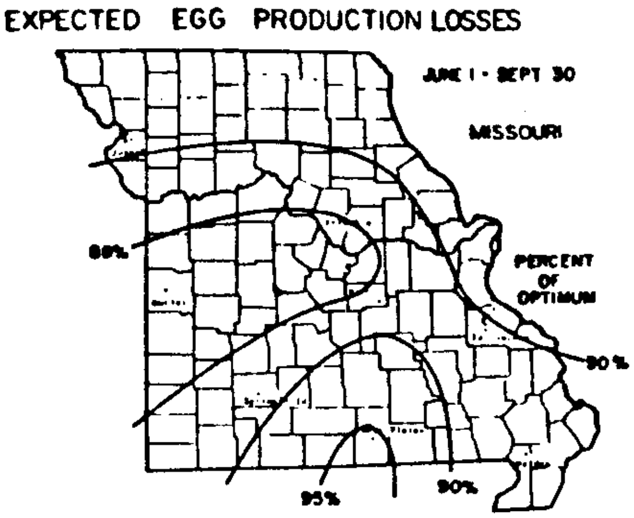


Figure A.5 - Expected egg production losses as percentages of optimum egg production in Missouri, USA, for shaded laying hens subjected to natural summer weather (1 June - 30 September) (Hahn, 1975)

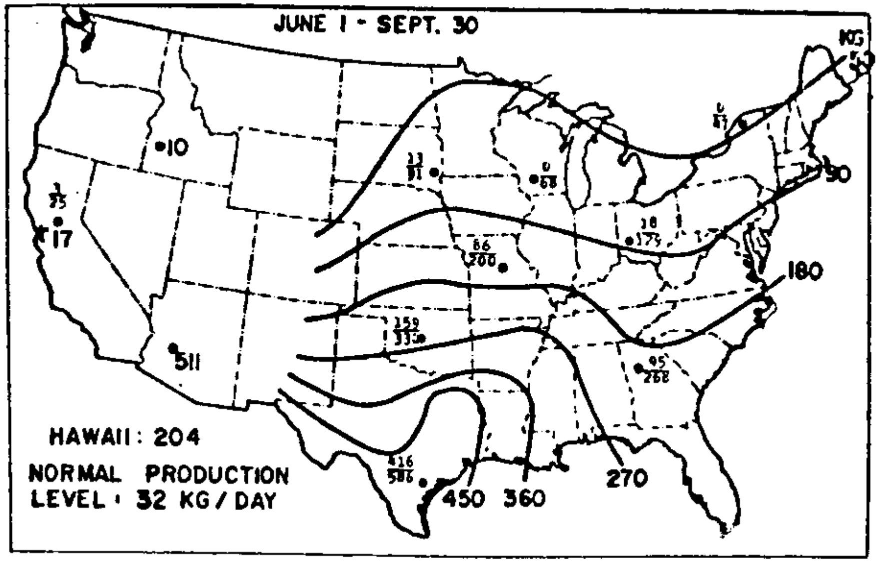


Figure A.6 – Expected summer season milk production losses (kg) for dairy cows with a normal production level of 32 kg/day during the 1 June – 30 September period (from Hahn and Osburn, 1970). Values by selected stations (e.g. 86/200) represent the 10th percentile and 90th percentile production losses (i.e. lowest and highest losses expected one year in 10) for that station, indicating the variability in production due to climate fluctuations (Hahn and Nienaber, 1976)

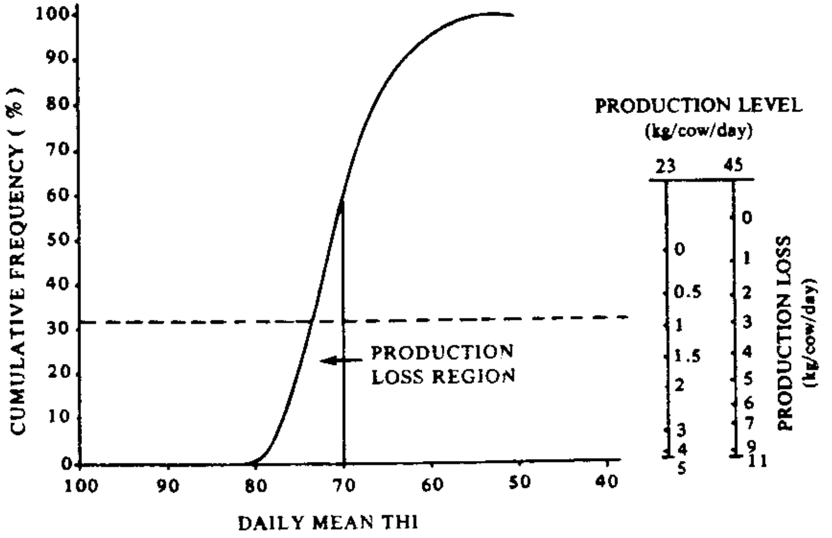


Figure A.7 – Empirical probablilty curve for production decline of Holstein cows at Columbia, Missouri, USA, based on 20-year distribution function of daily mean THI values (1 June – 30 September) (after Hahn and McQuigg, 1970)

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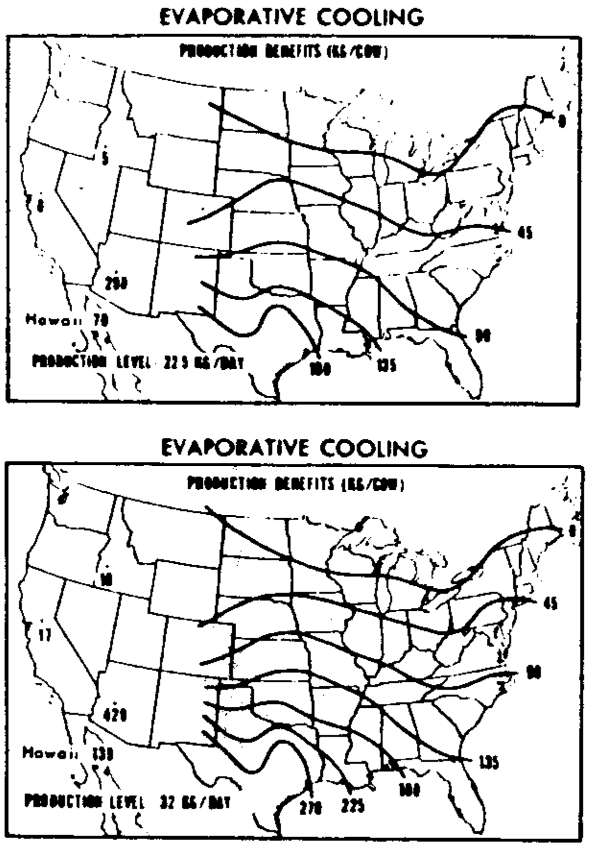

Figure A.8 - Expected production benefits resulting from evaporative cooling during the 122-day summer period 1 June to 30 September for cows normally producing 22.5 (top) and 32 kg/day (bottom) (adapted from Hahn and Osburn, 1970)

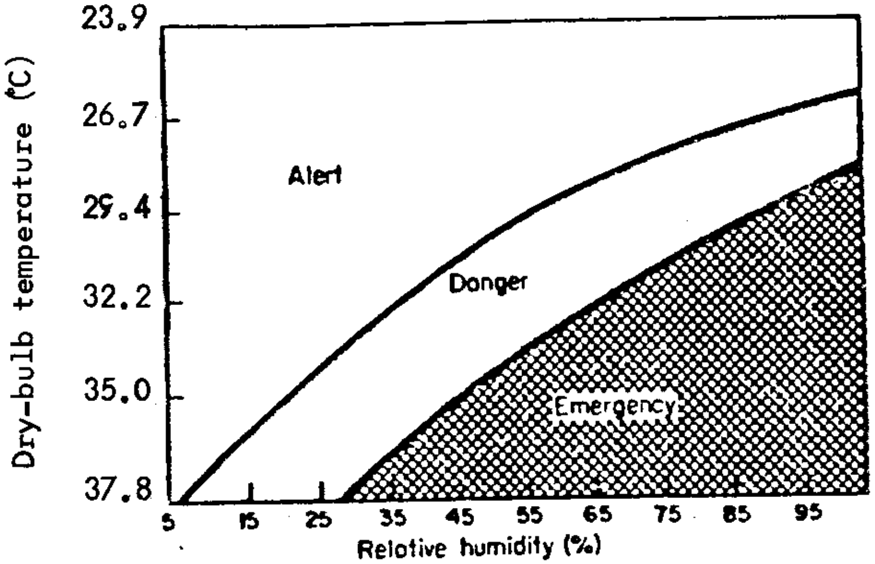

Figure A.9 - Temperature-humidity index (developed by the US Weather Bureau) as presented in a livestock safety booklet distributed by Livestock Conservation Inc., USA

TABLE A.1

Weight gain comparisons of six breeds of cattle at two environmental temperatures

(Johnson, 1982)

Species	Air temper- ature °(C)	Weight at 4 months (kg)	Weight at 12 months (kg)	Total gain for 8 month period (kg)	Difference in gain from 10°C values (kg)
Santa	10	126.1	342.9	216.8	
Gertrudis	27	128.4	313.0	184.6	-32.2
Brahman	10	112.9	285.8	172.8	
	27	116.6	197.6	181.0	+8.2
Shorthorn	10	93.0	298.5	201.9	
	27	73.9	209.1	135.2	-66.7
Holstein	10	103.5	333.3	203.3	
	27	95.3	302.7	207.4	-22.9
Brown Swiss	10	74.2	303.3	229.1	
	27	89.0	310.2	221.2	-7.9
Jersey	10	65.5	210.0	144.5	
	27	56.7	197.3	140.6	-3.9

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TABLE A.2

Environmental heat effects on growth, feed intake, ratio of feed intake to weight gain, tri-iodothyronine, and rectal temperature (Johnson, 1982)

Temperature Humidity Days	20°C 50% 0-21	35°C (heat) 50% RH 22-57	20°C 50% 58-82
Weight gain, kg/day	.97 ± .06	.70 ± .09	1.42 ± .09
Feed intake, kg/day	5.60 ± .3	5.81 ± .3	7.29 ± .6
Feed/weight gain, kg/day	6.07 ± .2	8.75 ± 1.2	5.19 ± .3
Tri-iodothyronine, ng/ml (plasma)	1.65 ± .2	1.16 ± .2	2.20 ± .2
Rectal temperature, °C	39.24 ± .1	40.32 ± .07	39.00 ± .14

TABLE A.3

Rectal temperature, thyroxine, and progesterone in pregnant cows (3rd trimester) exposed to environmental heat stress (Johnson, 1982)

Days	20°C 50% RH 1-7	32°C 50% RH 8-14	20°C 50% RH 15-21
Rectal temperature, °C	38.8 ± .07	39.9 ± .4	38.6 ± .2
Plasma thyroxine, ng/ml	53.82 ± 3.1	37.8 ± 9.0	13.72 ± 6.3
Plasma progesterone, ng/ml	6.38 ± .7	6.67 ± .8	4.79 ± .5

TABLE A.4
Currently available functional relationships between weather events and performance of dairy cows and poultry (Hahn, 1982(a))

DAIRY COWS

1. Hay consumption decline (HDec) with constant grain intake

$$\text{HDec} = -\,28.19 + 0.391\ \text{THI}$$

where: HDec = absolute decline in hay consumption (kg/cow/day);
THI = daily mean temperature-humidity index value* above 72.

2. Milk production decline (MDec)

$$\text{MDec} = -1.075 - 1.736\ \text{NL} + .02474\ (\text{NL})(\text{THI})$$

where: MDec = absolute decline in milk production (kg/day/cow);
NL = normal level of production (kg/day);
THI = daily mean temperature-humidity index value* above 70.

3. Conception rate (CR)

$$\text{CR} = 388.3 - 4.62\ \text{THI}$$

where: CR = conception rate (in terms of delivered calf) (%);
THI = daily mean temperature-humidity index value* above 69.

POULTRY

1. Laying hen egg producton (Egg)

$$\text{Egg} = +\,0.556 + 0.0389\ t_{db} - 0.00179\ t_{db}^{2} + 0.0000186\ t_{db}^{3}$$

where: Egg = number of eggs/day/hen (based on 2.25 kg Rhode Island Red hens);
t_{db} = ambient dry-bulb temperature (°C);
$(5° \leq t_{db} \leq 30°)$.

2. Broiler growth rate (BADG)

$$\text{BADG} = -\,6.338 \times 10^{-2} + 1.963 \times 10^{-2}\ (W) + 3.055 \times 10^{-3}\ (\text{THI})$$
$$-\,2.521 \times 10^{-5}\ (\text{THI})^{2} - 9.061 \times 10^{-5}\ (\text{THI})\ (W)^{2}$$

where: BADG = average daily gain of broilers between 0.5 and 1.5 kg body weight (kg/bird/day);
W = body weight of birds (kg);
THI = daily mean temperature-humidity index value* above 70.

* THI is a derived statistic computed from the relation:

$$\text{THI} = t_{db} + .36\ t_{dp} + 41.2$$

(t_{db} = dry-bulb temperature, °C; t_{dp} = dew-point temperature, °C)

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TABLE A.5

Summer season milk production declines and evaporative cooling benefits
(Normal production level = 32 kg/day)
(from Hahn, 1981)

Location	Projected seasonal milk production, kg/cow			
	Decline		Evaporative cooling	
	Expected*	1980	Expected*	1980
Atlanta, GA	197	425	124.3	292.1
Boise, ID	10	2	10.0	1.8
Cheyenne, WY	38	0	38.0	0
Columbia, MO	149	282	99.8	252.2
Dallas, TX	343	644	268.5	565.2
Dayton, OH	87	122	54.9	93.9
Memphis, TN	191	568	141.5	396.0
Oklahoma City, OK	254	437	179.6	423.7
Phoenix, AZ	511	616	429.1	598.3
Sacramento, CA	17	15	16.8	14.5
Sioux Falls, SD	57	55	44.4	51.7

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* Long-term expected (average) value based on several years of climatological records: in half the years, the seasonal production loss should be above this value; in half the years, seasonal product in loss should be below this value.

TABLE A.6

Profitablility analysis of air conditioning and evaporative cooling for a 100-cow dairy herd in the Memphis, Tennessee (USA) area

(32 kg/day normal level of production)

(Hahn and Osburn, 1970)

PROFITABILITY ANALYSIS OF AIR CONDITIONING AND EVAPORATIVE COOLING FOR A 100-COW DAIRY HERD IN THE MEMPHIS, TENN., AREA

(70 lb/day normal level of production)

Cooling method	Milk price, dollars per cwt	Hay cost, dollars per ton	Air cond. req'd., tons per cow	Installed cost, total dollars	Electric energy used kwh per season	Energy cost, dollars per kwh	Water cost‡, dollars per 100 gal	Cost of insulation, dollars	System life, years	Interest rate, percent	Total initial investment	Total discounted returns	Net profit (loss)	Benefit-cost ratio
Air Conditioning*	5.00	25	0.5	17,500	135,000	0.01	....	1,000	15	5	$18,500	$14,371	$(4129)	0.777
	5.50	25	0.5	17,500	135,000	0.01	....	1,000	15	5	18,500	17,069	(1431)	0.923
	6.00	25	0.5	17,500	135,000	0.01	....	1,000	15	5	18,500	19,768	1268	1.068
	6.00	35	0.5	17,500	135,000	0.01	....	1,000	15	5	18,500	18,523	23	1.001
	6.00	25	0.6	21,000	162,000	0.01	....	1,000	15	5	22 000	17,827	(4173)	0.810
	6.00	25	0.5	22,500	135,000	0.01	....	1,000	15	5	23,500	20,793	(2710)	0.885
	6.00	25	0.5	17,500	135,000	0.015	....	1,000	15	5	18,500	14,164	(4336)	0.766
	6.00	25	0.5	17,500	135,000	0.01	....	2,000	15	5	19,500	19,972	472	1.024
	6.00	25	0.5	17,500	135,000	0.01	....	1,000	10	5	18,500	15,971	(2529)	0.863
	6.00	25	0.5	17,500	135,000	0.01	....	1,000	15	6	18,500	18,576	76	1.004
Evaporative Cooling†	5.00	25	....	1,500	5,250	0.01	.05	1,000	5	5	$ 2,500	$ 5,057	$2,557	2.023
	5.50	25	....	1,500	5,250	0.01	.05	1,000	5	5	2,500	5,711	3,211	2.284
	6.00	25	....	1,500	5,250	0.01	.05	1,000	5	5	2 500	6,364	3,864	2.546
	6.00	35	....	1,500	5,250	0.01	.05	1,000	5	5	2,500	6,123	3,623	2.449
	6.00	25	....	2,000	5,250	0.01	.05	1,000	5	5	3,000	6,483	3,483	2.161
	6.00	25	....	2,500	5,250	0.015	.05	1,000	5	5	3,500	6,512	3,012	1.861
	6.00	25	....	2 500	5,250	0.02	.05	2,000	5	5	4,500	6 660	2,160	1.480
	6.00	25		2 500	5,250	0.02	.10	1,000	5	5	3,500	5,818	2,318	1.662
	6.00	25	....	2 500	5,250	0.02	.05	1,000	10	5	3,500	10,810	7,310	3.089
	6.00	25	....	2 500	5,250	0.02	.05	1,000	5	6	3,500	6,048	2,548	1.728

* Predicted seasonal increase in milk production = 6.5 cwt per cow; added hay intake = 0.15 ton per cow.
† Predicted seasonal increase in milk production = 3.8 cwt per cow; added hay intake = 0.07 tons per cow.
‡ 125 gal per hr of operation.

APPENDIX B

HOUSING FOR ANIMAL PRODUCTION

B.1 Model of livestock production

Animals necessarily generate metabolic heat and this must be dissipated to the environment by the processes of conduction, convection, radiation and evaporation (Table B.1). Over a limited range of environments, commonly denoted by the "thermoneutral zone" (TZ), steady heat balance can be achieved (Smith, 1970; Mount, 1979; Sainsbury, 1981; Vermorel, 1982; Berbigier, 1982) (Figures 1.4 and B.1). For a given class of livestock, TZ will be a function of age and level of feed intake; it is particularly narrow for young stock (Figure B.2). Bounding TZ are the upper and lower critical temperatures (Bianca, 1976; Clark, 1981; Hahn, 1982(a)) and beyond TZ the animal will experience stress (Figure 1.4).

Smith (1974) has discussed a simplified energy equation for livestock production:

$$Y = \text{function of } [I - (M_b + M_c + M_d)]$$

where: Y = productivity - measured by milk, eggs or growth production;
I = the metabolizable energy in the feed intake;
M_b = the "base metabolism" in a resting animal in thermoneutral conditions;
M_c = the energy expenditure due to departures from "thermoneutrality"; and
M_d = energy expenditure due to movement.

Thermal imbalance between livestock and the environment represents an adverse influence on performance. However, by housing livestock properly, adverse effects on consumption, I, and M_c are reduced. A reduction in M_d will also occur. Hence, production (Y) per unit of intake (I) is higher.

The questions that must then be asked are: How frequently, by how much, in what season, is I so depressed or M_c so raised that heavy investment in protecting livestock is justified?

B.1.1 Likelihood estimates

Such investment questions can be appraised by climatological records, which provide a relatively easy means of assessing how often singular events may occur in the outdoor situation. The technique is illustrated in Appendix A, section 3 of this report and in Chapters 6 and 7 of the Guide to Agricultural Meteorological Practices (WMO, 1981). Smith (1974) explores methods of operational research in assessing these housing investment questions (see Appendix C, section 1.2).

B.1.2 Design temperatures

An "acceptable" level of risk to production can be achieved by designing housing which maintains temperatures within specific ranges.

"Design temperatures" are based on the frequency distribution of hourly temperatures and are expressed as those temperatures exceeded during a certain percentage of hours during summer or winter. Smith (1981), for example, quotes the 2.5 per cent design dry-bulb and wet-bulb temperatures appropriate to poultry production in tropical and sub-tropical climates (Table B.2). Other workers who discuss this rational selection of design temperatures for livestock housing applications are Thom (1960), Hahn et al. (1971), Schweizerische Stall-Klima Norm (1983), Stevens and Le Duc (1977), Bresk and Rehmann (1983) and Hahn (1983). Bruce (1983) details the 1, 5, 10, 90, 95 and 99 per cent values for sites in the United Kingdom (Table B.3).

B.2 Air hygiene

Complementary to a favourable thermal environment is a hygienic environment. At low external temperatures, house ventilation rates, required for design procedures which consider only internal temperatures, are likely to be incompatible with good air hygiene and animal health (Smith, 1983).

B.2.1 Airflow patterns and ventilation

The ventilation of livestock housing has been the subject of intensive study. Mitchell (1976), B.R.E. (1978), Sainsbury and Sainsbury (1979) and others have investigated designs for mechanically and naturally ventilated housing. Bruce (1978), for example, has established design criteria for the optimum "stack effect" for cattle and pig housing, suggesting various geometries of openings. An essential input is the likelihood of various external temperature regimes. Such changes may occur between day (Figure B.4(a)) and night (B.4(b)) as well as between seasons of the year.

The patterns of air movement in a livestock building form the link between external climate, the ventilation system and the microclimate around the livestock (Randall, 1975). Here is a potential role for meteorological inputs as operational indicators of air quality. However, siting and external wind, temperature and humidity affect both entry conditions and factors influencing patterns of internal air movement even in nominally "controlled environment" houses (Figure B.3). Randall (1975) also illustrates that internal fittings exert a profound influence on the flow pattern (Figure B.5).

B.3 Siting

While housing design has received a lot of attention, local siting of an enterprise has been neglected. Yet site selection in generally marginal areas for a particular type of enterprise is clearly important and may swing the balance between failure and success. Although general guidelines are offered, for example, by Rogerson (1971) (Figure B.6) and Hahn et al. (1962), the problem is often that housing sites are chosen as a compromise between the requirements for reasonable access, drainage and proximity to power supplies and other buildings. Site-specific meteorological inputs, if considered at all, are often victims of these logistic and short-term economic factors. In the long term, such neglect may prove expensive.

B.3.1 Strategies of site planning

The general problems of characterizing the biometeorological environments so as to map areas appropriate to various forms of livestock housing enterprise are discussed in Chapter 1, sections 1.3.2.1 and 1.3.2.2.

As examples of mapping for strategic planning of housing, Figure B.7 shows average values of the temperature humidity index for contrasting climates (Johnson, 1980), while Butchbaker <u>et al</u>. (1972) give classifications of beef housing and waste management systems in terms of local climate data using mean annual temperature and "moisture deficit" (Figure B.8). (The "moisture deficit" is calculated as the annual evaporation from an open water surface minus annual rainfall and is from a slurry lagoon or feedlot surface.) Other examples are given in Chapter 1 and in this appendix. Appropriate meteorological advice at an early stage in the planning of a livestock housing enterprise can therefore make a major contribution to livestock health and productivity.

B.4 Forecasts for tactical decision-making

Current or forecast weather information is particularly important at vulnerable stages in the life cycle of housed livestock. Weather forecasts at parturition could guide tactical decisions on activating heat sources in cold weather or sprays, fans and other cooling devices in hot weather. One such example is the livestock weather safety statements of the US Weather Bureau based on forecasts of high temperature, radiation levels and high humidity. These allow livestock managers to consider appropriate action such as wetting stock and minimizing exposure to solar radiation.

Other examples of the tactical use of weather forecasts for the benefit of housed stock and poultry are given in Appendix C.

B.5 Forms of environmental modification

B.5.1 Housing

Guidance on a broad spectrum of livestock housing and environmental modification procedures to mitigate climate limitations is available (Hahn <u>et al</u>., 1971; Kaul, 1975; Sainsbury and Sainsbury, 1979; Clark, 1981; Paesch, 1983) (Figure B.8 and Tables B.2 and B.3). For extensive production, simple shelters may suffice and MacFarlane (1981) and Gatenby (1985) discuss such structures for a variety of livestock in hot climates in terms of the heat budget for sheltered stock (Figure B.9).

In the tropics there is evidence of significant increases in performance efficiency when shades or shelter are introduced into dry-lot feeding schemes. The benefits of shade provision may well be questionable, however, in hot, humid environments that are associated with low air movement, if the congregation of stock further restricts that air movement and hence evaporation and convection.

Various practical considerations may influence the choice of orientation for housing or shelter. A north-south orientation may be preferred for the housing of dairy and beef cattle in warm climates with high solar radiation, because the relatively short period of shading of a particular ground area during the daily radiation cycle will allow the ground to dry out, minimizing sanitation problems. However, an east-west orientated shelter may intercept more solar radiation and so provide a "cooler" environment in which ground temperature will also be lower (Figure B.10).

Semi-intensive and intensive enterprises demand increasingly sophisticated shelters involving, for example, artificial cooling techniques (wallows, sprinklers, wet pads, fans).

The benefit-cost aspects based on climate must be thoroughly investigated: Gatenby (1985) concludes that complete environmental control in hot climates is rarely justified or achievable. Indeed, in cost-benefit terms alone for the animal production system, controlled environment housing is not justified for many classes of livestock in cold or temperate zones.

B.5.2 Shelterbelts and windbreaks

Caborn (1965) drew attention to the value of assessing geomorphic and natural shelter (e.g. by tatter flag studies (Thomas (1959)) but warn, nonetheless, that shelter without access to feed may be to no avail in severe blizzard conditions.

Studies on in-lamb Welsh mountain ewes by Winfield *et al*. (1969) indicated a role for shelter but also a need for quantifying both exposure and its associated influences on productivity. Alexander *et al*. (1980) and Lynch and Donnelly (1980), too, show that meteorological inputs in the design and siting of windbreaks have an important role in increasing pasture and animal production in temperate areas of Australia. Sturrock (1984) describes New Zealand and Australian shelter studies, pointing to specific research needs for data relevant to local farming conditions which will enable the economic and management values of shelterbelts to be assessed. Progress in this direction has been reported by Bruce (1984) who has used physical and mathematical models to measure and simulate the effect of temperature, wind, net radiation and precipitation on cattle. The work has made possible the prediction of the effect of climate and types of shelter; thus the value of shelter has been expressed in terms of liveweight loss and feed requirement.

The influence of shelterbelts on livestock production is clearly an area which needs much more study, as recognized in WMO (1964).

*

* *

START INDEX

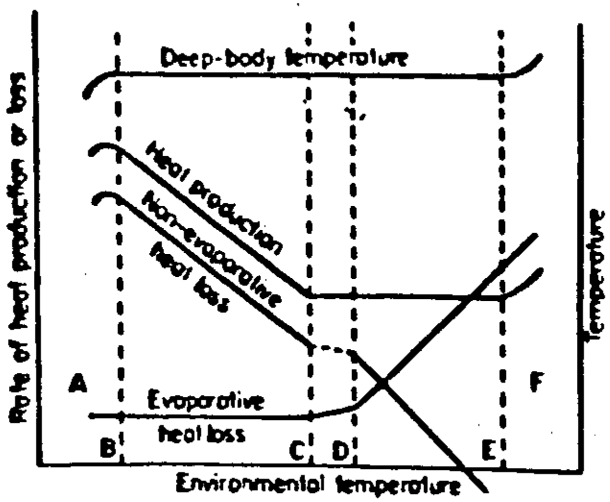


Figure B.1 - Relationship between heat production, evaporative and non-evaporative heat loss and deep-body temperature in a strict homeotherm: A = zone of hypothermia whose border is defined by B; F = zone of hyperthermia whose border is defined by E; C = lower critical temperature; D = temperature of marked increase in evaporative loss (upper critical temperature); CD = zone of minimal thermoregulatory effort; CE = zone of minimal metabolism (the thermoneutral zone) (Mount, 1974)

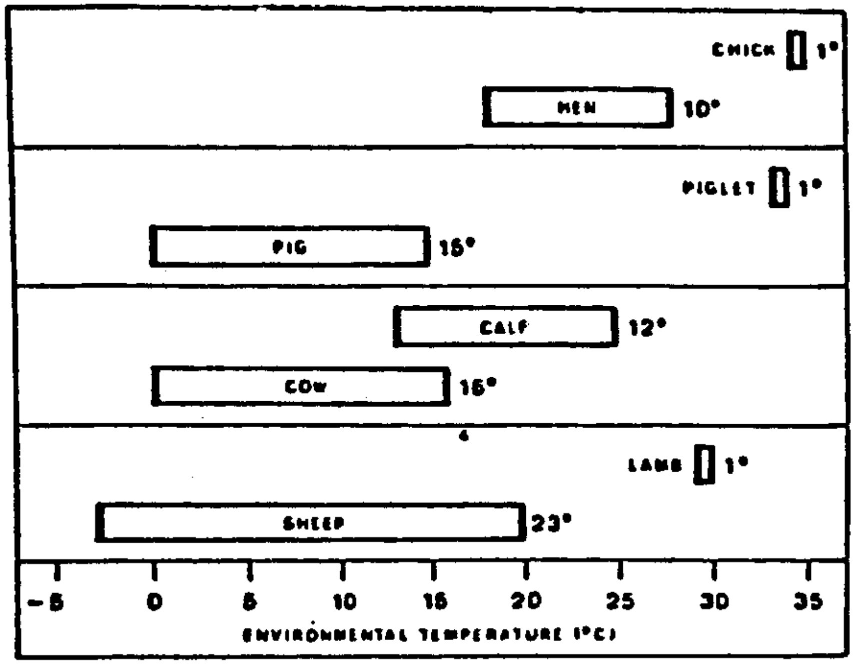


Figure B.2 - Zones of thermal indifference of young (newborn) and adult animals of four species. The lower limit of the zone represents the lower critical temperature, the upper limit the environmental temperature at which evaporation begins to increase. The figures after each bar indicate the width of the zone in °C (Bianca, 1976)

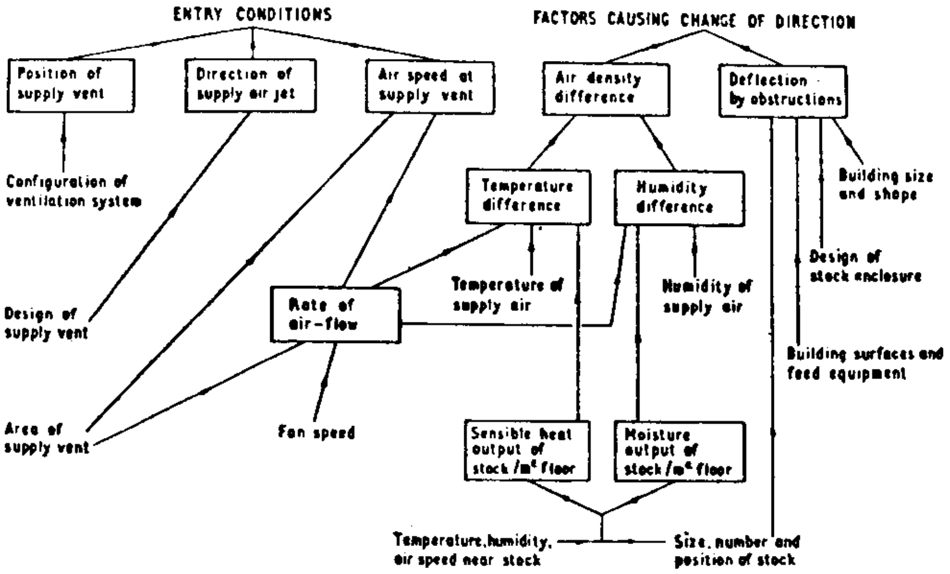


Figure B.3 - Factors affecting airflow patterns (Randall, 1975)

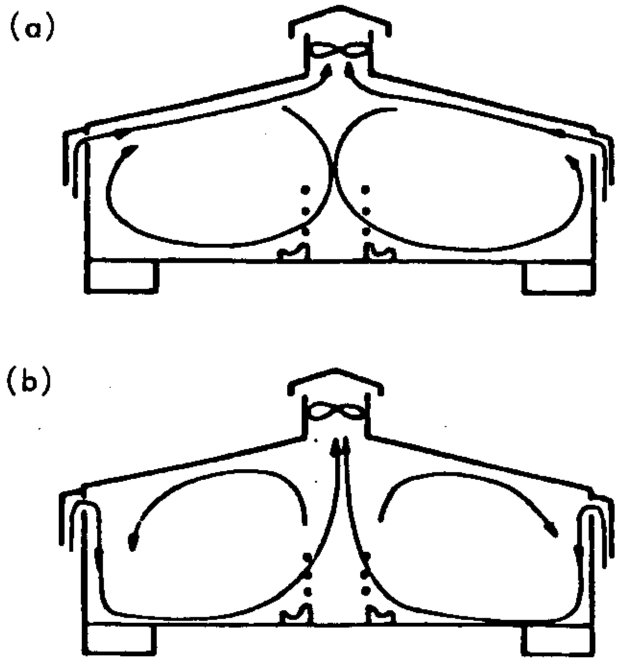
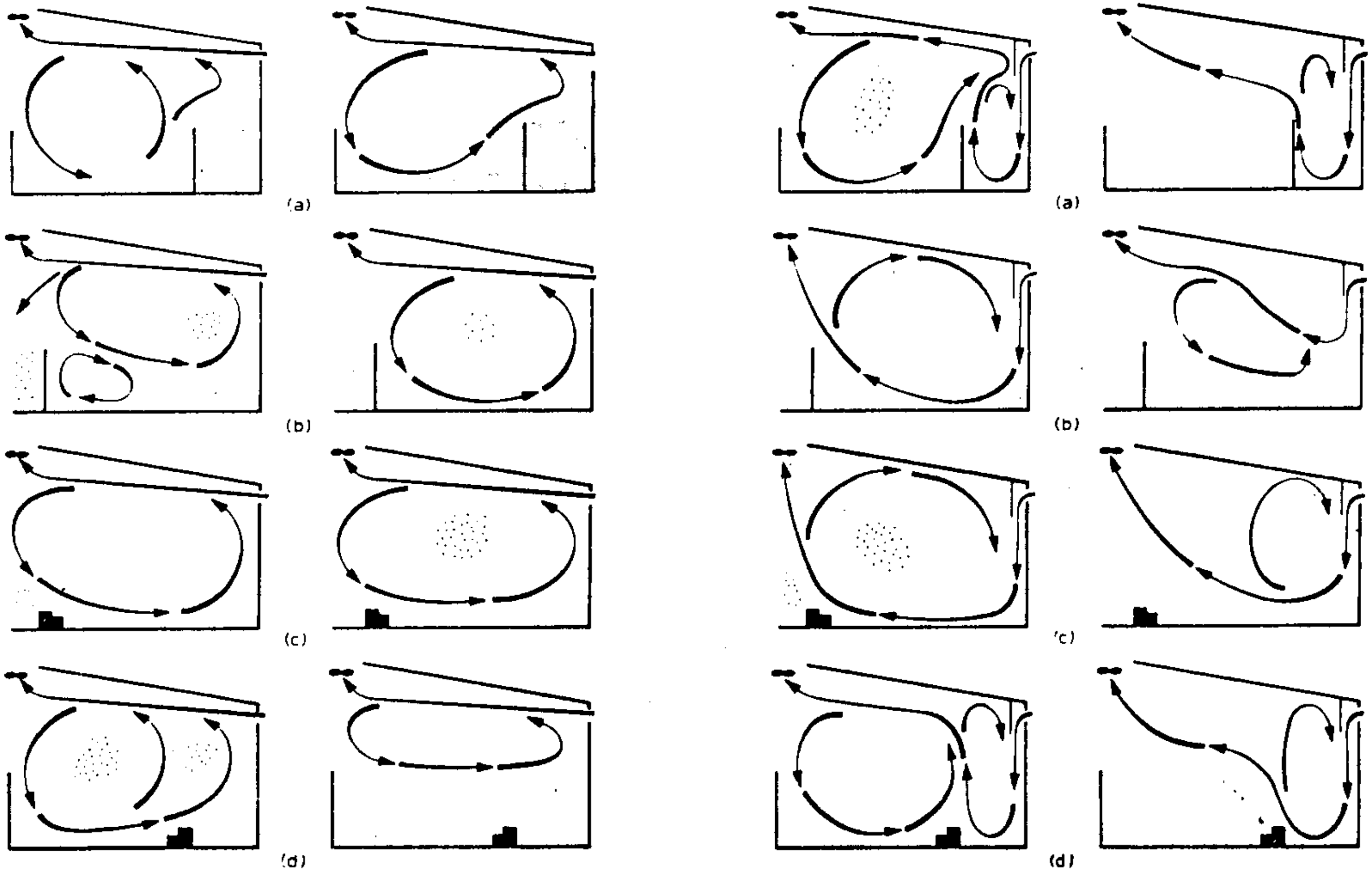


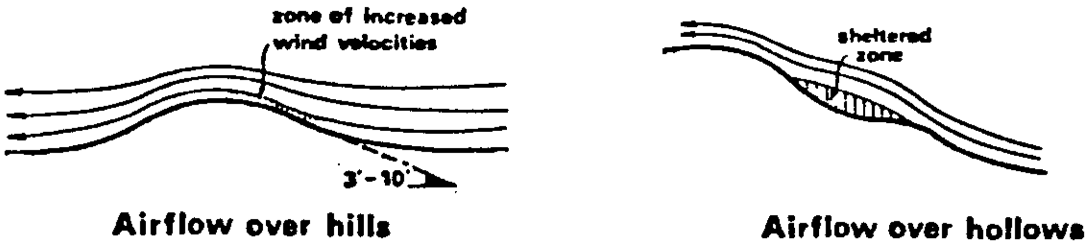
Figure B.4 - Diagram of the reversal of direction of airflow pattern due to changes in external temperature: (a) hot; (b) cold (Sainsbury, 1981)



Air introduced horizontally from the eaves, isothermal.
Left, 0·68 m³/s; right, 0·14 m³/s

Air introduced downwards from the eaves, isothermal.
Left, 0·68 m³/s; right, 0·14 m³/s

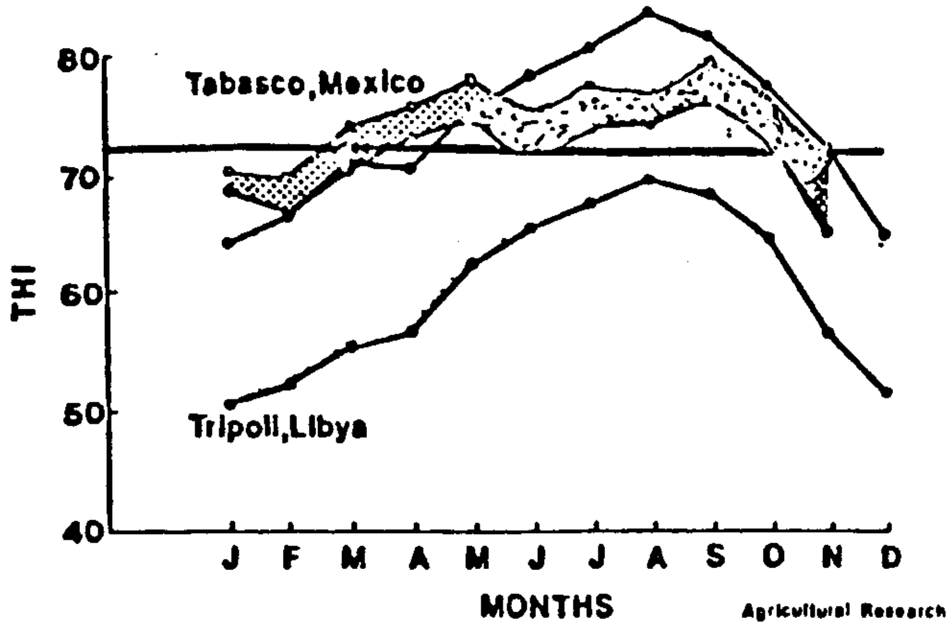
Figure B.5 - Sample circulation patterns by internal fittings (Randall, 1975)



Airflow over hills

Airflow over hollows

Figure B.6 - Airflow over hills and hollows: an influence on siting of housing (Rogerson, 1971)



Agricultural Research Centre, Tripoli, Libya
Colegio Superior De Agricultura Tropical.
Cardenas, Tabasco, Mexico

Figure B.7 - Average maximum and minimum monthly THI for contrasting climates to provide an estimate of the suitability of climates for dairy cows whose performance is adversely affected above THI = 72. Although the maxima for June, July, August and September are higher for Tripoli than for Tabasco, the days above 72 are about 225 per year at Tabasco compared with about 72 per year at Tripoli (Johnson, 1980)

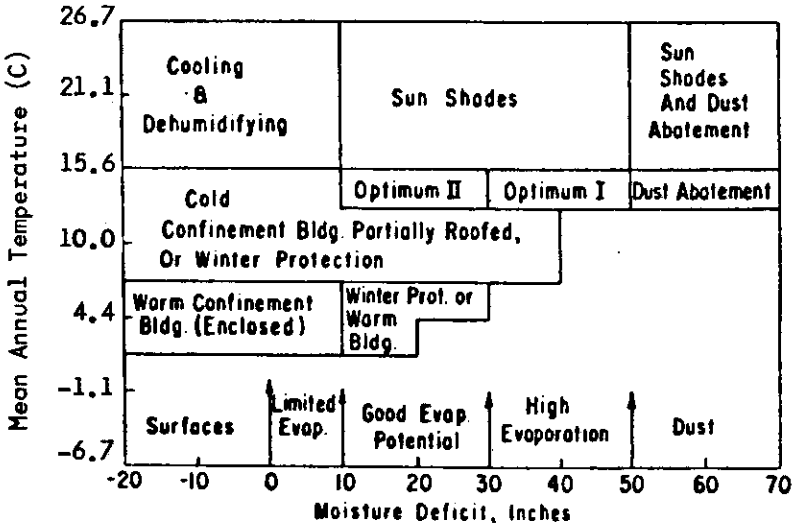


Figure B.8 – Beef housing needs classified in terms of local climatic data on mean annual temperature and annual moisture deficit (evaporation from an open water surface minus rainfall) (Butchbaker et al., 1972)

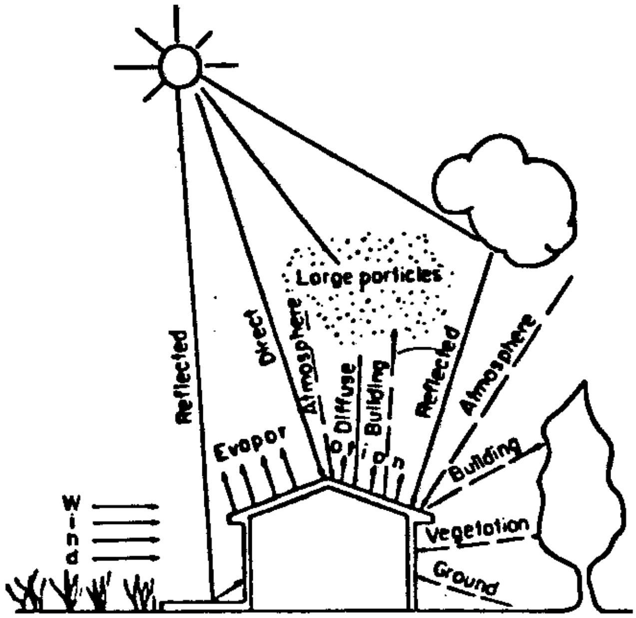


Figure B.9 – Channels of heat transfer for a building and the environment: ——— = short-wave radiation; ------- = long-wave radiation (McFarlane, 1981)

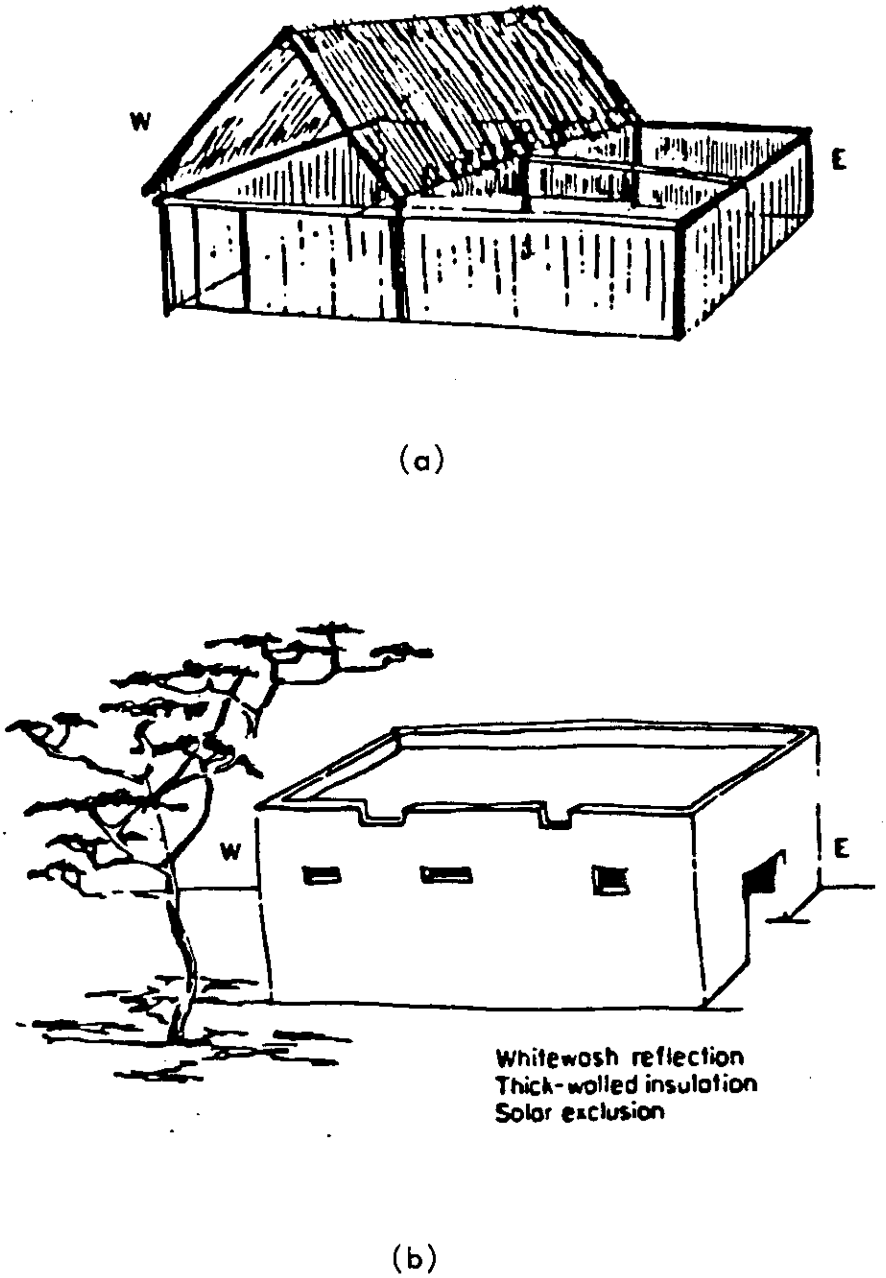


Figure B.10 - (a) Indoor-outdoor cattle shed in Kenya. The cool, shaded area under the thatch has good airflow. The outdoor area is suitable for cool-season living; (b) Tropical desert building in Somalia with small windows, thick walls and white reflective surfaces. Shade trees to the west. There is not much air movement but, if the air temperature is 40°C or more, it is better outside than flowing through the building

APPENDIX B

TABLE B.1

Factors influencing energy transfer from the surface of an animal

(from Hahn, in Johnson, 1976)

Factor	Mode of heat transfer			
	Radiation	Convection	Conduction	Evaporation
Surface area of animal	1	x	2	3
Temperature of animal surface	x	x	x	4
Temperature of surroundings	x		5	
Temperature of air		x		x
Velocity of air		x		x
Vapour pressure of air				x
Shape factor of radiation source or sink	x			
Emissivity of animal surface	x			
Conductivity of surroundings			5	

Notes:

1 - Area of animal directly exposed to the radiation source or sink
2 - For standing animals, conduction heat transfer is negligible; for animals lying down, the area of animal surface in contact with the supporting structure becomes a factor.
3 - The wetted area of the animal surface, including the respiratory passages
4 - The temperature of the animal surface is an indirect factor, since vapour pressure is a function of temperature.
5 - Only that portion of the surroundings actually in contact with the animal

TABLE B.2

The 2 1/2% design temperatures for the summer and winter months and the daily range of dry-bulb temperatures at selected locations with tropical and sub-tropical climates

(from ASHRAE Handbook and Product Directory, Fundamentals Volume, 1977)

Location		Climate type	2 1/2% design temperature (°C)			
			Winter dry-bulb	Summer dry-bulb	Summer wet-bulb	Dry-bulb daily range
Kisangani, Zaire	0°N	Af	20.0	32.8	26.7	10.6
Singapore	1°N	Af	22.2	32.8	27.2	7.8
Belem, Brazil	1°S	Am	21.7	31.7	26.1	10.6
Columbo, Sri Lanka	7°N	Am	21.1	31.7	26.7	8.3
Manila, Philippines	15°N	Aw	23.3	33.3	27.2	11.1
Recife, Brazil	8°S	Aw	21.1	30.6	25.5	5.6
Baghdad, Iraq	33°N	BWh	1.7	43.9	22.2	18.9
Karachi, Pakistan	25°N	BWh	10.6	36.7	27.8	7.8
New Delhi, India	29°N	BSh	5.0	41.7	27.8	14.4
Accra, Ghana	6°N	BSh	20.6	32.2	26.1	7.2
Brisbane, Australia	29°S	Cfa	8.3	31.1	24.4	10.0
Buenos Aires, Argentina	35°S	Cfa	1.1	31.7	24.4	12.2
Perth, Australia	32°S	Csa	5.6	35.6	23.3	12.2
Athens, Greece	38°N	Csa	2.2	33.9	21.7	10.0

Notes:

- Latitudes are given to the nearest degree.
- Climate type according to the Koeppen-Geiger classification system

TABLE B.3

Design temperatures (t) for the United Kingdom (Bruce, 1983)

Location (see Table 1 and Figure 2)	t_1* (°C)	t_5 (°C)	t_{10} (°C)	t_{90} (°C)	t_{95} (°C)	t_{99} (°C)
1 Wick	−2.3	0.5	1.9	13.0	14.2	16.7
2 Stornaway	−1.3	1.1	2.6	13.1	14.2	16.7
3 Aberdeen	−3.3	0.0	1.4	14.6	16.5	20.4
4 Tiree	1.0	2.6	4.0	13.7	15.8	17.2
5 Leuchars	−2.7	0.3	1.7	15.0	16.7	20.1
6 Edinburgh	−3.0	0.1	1.8	15.4	17.1	20.8
7 Prestwick	−3.0	0.2	2.1	15.2	16.8	20.8
8 Boulmer	−2.0	0.5	1.7	14.4	16.1	18.9
9 Eskdalemuir	−5.6	−1.5	0.2	13.9	16.0	21.0
10 Carlisle	−3.4	0.2	1.9	15.8	17.7	21.9
11 Belfast	−1.9	0.9	2.4	15.5	17.2	21.3
12 Leeming	−3.2	0.2	1.7	16.4	18.4	22.8
13 Manchester	−2.0	0.8	2.5	16.7	18.8	23.4
14 Valley	0.2	2.9	4.5	15.7	17.1	21.4
15 Waddington	−2.5	0.1	1.5	16.6	18.8	23.1
16 Coltishall	−1.8	0.8	2.4	17.0	19.1	23.0
17 Wyton	−2.4	0.4	2.0	17.4	19.7	24.2
18 Aberporth	−0.4	2.2	3.7	15.2	16.7	19.8
19 Brize Norton	−2.7	0.2	1.9	17.3	19.7	24.1
20 Cardiff	−1.5	1.2	2.9	16.5	18.3	22.5
21 London	−3.1	0.0	1.8	17.7	19.8	24.4
22 Bournemouth	−3.2	0.1	2.3	17.4	19.4	23.5
23 Plymouth	−0.3	2.8	4.6	16.6	18.1	21.6

* Temperatures were below t_n for n% of the time.

† Temperatures are not adjusted to sea level. To adjust for altitude allow 0.5 and 0.7 deg C per 100 m for low and high temperatures respectively (1).

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APPENDIX C

STRESS

This appendix begins with a discussion of direct thermal stress, introduced in Chapter 1, section 1.4.1.1.

C.1 Strategies against thermal stress

Though self-selection will obviously occur in extreme environments, positive programmes of genetic selection and improvement for indigenous stock can help a flock or herd to cope with hostile climates and weather events (Trail and Gregory, 1981; Johnson, 1982).

The importation of exotic stock and blood lines (i.e. from somewhat different climate zones) in order to upgrade local animal production in the tropics is commonly a long-term and difficult process, not least because high levels of animal production imply high levels of production of body heat which has to be dissipated to the environment (Appendix B). (Parasitism may also be a further problem.) In temperate zones, however, the ability to rapidly utilize feed or mobilize body reserves is an advantage upon which genetic selection can build.

C.1.1 Hyperthermia

High temperatures and high radiation levels can be particularly stressful to pigs and poultry which do not have a sweating ability. Where animals cope with heat stress by panting, air humidity also becomes a significant factor in the assessment of environments.

C.1.1.1 Swine

Primault (1971) and Smith (1975) showed the additional influence of a range of day-time maximum temperatures and relative humidities in stressing pigs which were being transported (one should comment that breed is important here). Morrison et al. (1970) described a method of estimating summer production losses in swine in the USA. A functional relationship between production losses and environment was established (Figure C.1(a) and (b); these losses (gain reduction factors) were quantified by reference to the frequency of occurrence of the combined parameters temperature and relative humidity (THI - Table A.4) as illustrated in Figure C.1(c) and Figure A.4.

THI was also used by Fehr et al. (1982) for assessing the value of cooling in limiting stress in swine (Table C.1), while Beckett (1965) describes an "effective temperature" index (a combination of air temperature and air velocity) (Smith, 1970) for evaluating hog environments.

Production losses in lactating Holstein dairy cows, predicted by Hahn and McQuigg (1967), are discussed in Appendix A, section A.4 (Figures A.6 and A.7).

C.1.1.3 Poultry

Cochrane (1984) describes a simple model of heat and moisture exchange for six to eight week old broiler chickens in the United Kingdom, which he uses to estimate environmental temperatures which the bird can tolerate (Table C.2(a) and (b). He compares these with United Kingdom air temperatures experienced in incidents which resulted in deaths due to heat stress (Table C.2(c)). It seems probable that deaths in these birds could exceed 10 per cent when air temperatures exceed 30°C for several hours. Corrections are made for the case of crowding or clustering when the birds's effective surface area is reduced by, say 25 or 50 per cent. The tolerance temperatures are then as low as 15-20°C (Table C.2(e) and (f)). With adequate ventilation and well-separated bird houses, temperatures of 28-30°C may be tolerated without stress.

The United Kingdom Meteorological Office already offers a tactical warning forecasting scheme in the broiler industry (with a criterion of four or more hours of temperatures above 23°C). Cochrane's data confirm the criterion and, in addition, point to the birds' habit of sitting on the floor in groups as counter-productive. Any management measures which will cause the birds to stand up and move apart and, if possible spread their wings to some extent, will help the loss of sensible heat. Nichelmann et al. (1982) discuss housing control and nutrient manipulation for poultry improvement in the tropics.

C.1.2 Hypothermia

Smith (1974) describes a technique for assessing cold stress in steers and hence the need for housing. Using liveweight data for steers fed at maintenance in Ireland he defined a lower critical temperature, T_c (Figure C.2). This presentation has enabled cold stress to be compared across the United Kingdom although the approach could be applied to other classes of livestock on a world basis. From a sample decade (Table C.3), Smith calculated that the weight loss associated with more extreme seasons could be double that for the average season.

Using these data in conjunction with the cost of various management options and the value of the animal production under various regimes, Smith (1974) drew up a decision matrix (Table C.4). The specific outcome, $O_{t,s}$, of various treatments, t in various seasons, s, could then be assessed. By summing over the decade to find the average outcome, a strategy of optimum management/housing options could be established - another example of a technique for aiding rational decision-making (see Appendix A).

C.1.3 Indices of "warmth" and "coldness"

Primault (1982) presents mapped indices of "warmth" and "coldness" for Switzerland as a guide to shelter needs. The warmth index is expressed in terms of the mean (1901-1960) July and the mean annual maximum temperatures. The corresponding "index of coldness" is a function of the mean minimum for January and the mean annual minimum. Primault considers that these indices are of more value than "design temperatures" since the former imply a "duration" as well as a magnitude of warmth or coldness (Figure C.3).

C.1.4 Examples of the role of specialized weather forecasts in aiding tactical decision-making

C.1.4.1 Lamb wind-chill

A lamb wind-chill forecasting scheme operated by selected weather centres in southern England is described by Starr (1984). Farmers telephone in to receive a 24-hour wind-chill forecast from 0800 GMT in a form that allows the separate contributions of daytime and night-time weather to cold stress to be noted. Farmers report that they have adjusted their management in response to these forecasts by, for example, retaining lambs in-house for the critical period of high wind-chill and/or assigning weakling stock to more sheltered fields.

A similar scheme for sheep and lambs has been devised by the CSIRO Division of Animal Production in South Australia. The forecasting nomogram (Figure C.4) gives a basis for the issue by the meteorological services of a general warning. Again the need is for the education of farmers through Ministry of Agriculture extension services as to the potential benefits of the schemes; in the United Kingdom the annual cost of the service to the individual farmer is equivalent to the cost of the loss of three or four fat lambs.

The essential interaction between meteorological inputs and good husbandry is highlighted by Ellis (1984) in a report of the value of plastic coats to sheared sheep. Rainfall, temperature and wind speed are the important factors whose influences on heat loss are modified by the coats.

C.1.4.2 Drought

Powell (1984) (private communication) describes a drought watch operated by the Australian Bureau of Meteorology. If rainfall and temperatures are within the extreme decile for three consecutive months, then a "drought watch" statement is issued (Figure C.5). Probability rainfall analysis for subsequent months allows this information to be of use in such management decisions as: the number of cattle per unit area (depending on pasture prospects); the provision of supplementary feed; and the planning of water supplies.

C.2 Pasture quality

The effects of weather and climate on pastures and herbage can impose important indirect effects for levels of animal production and major opportunities exist for weather-based planning and decision-making in pasture management for grazing stock. Sustainable animal-based economies require adequate feed to be available outside the main growing season for grass or forage, implying careful husbandry of pastures and feed throughout the whole farming year. Weather and climate determine pasture growth (both quantity and quality) and numerical relationships are possible here. These in turn can provide advice on pasture utilization, i.e. stock diversity, pasture rotation, herbage conservation for the lean periods of the year, etc. (Ripley and Redmann, 1976; Job and Taylor, 1978; Roy, 1981; Demarquilly, 1982; Rosenberg *et al*., 1983; and Jones, 1983). These management techniques may also be linked to disease and parasitism avoidance.

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C.2.1 Arid land grazing

Of major impact in arid lands are the large animals: cattle, sheep, goats and in a few cases, horses, donkeys and camels. MacFarlane (1981), in particular, discussed the environmental physiology of the larger mammals. Although the diversity of natural grazing lands is considerable, their carrying capacity under existing conditions is invariably low and falls rapidly as aridity increases. Overstocking is all the more serious because the plant cover is so fragile and difficult to re-establish.

The range grasses vary in quality and quantity in different seasons, being more abundant and highly nutritious in the rainy season but quickly becoming sparse and of low nutritional value during the dry season. Herds and flocks lose weight and are increasingly susceptible to disease (Chapter 1, section 1.1). Accordingly, Matlock (1981) notes that "livestock grazing requires the basic maintenance and improvement of rangeland through controlled use and technology designed within the limits of local soil and climate characteristics".

Rangeland animals are of two types: grazers feeding primarily on low grasses and herbs, and browsers that feed primarily on leaves and stems of woody vegetation. It is important to graze arid ranges with livestock that make best use of this forage. The keys to effective range management in arid lands are therefore:

(a) A forage-management programme based on climate and soil potential which is in balance even during adverse years;

(b) A livestock-management system that maintains a herd or a flock that can be quickly adjusted to short forage supplies, but is as quickly increased during favourable years.

This second option provides husbandry challenges because of disease, parasites, poor nutritive value of feed, management practices, etc., but to balance these negative aspects the climate conditions are excellent for both maintaining animals in large open feedlots (where wastes are easily disposed of) and for milk and growth production. Such interactions between crop and livestock production are detailed by Hall *et al*. (1979).

C.2.2 Hill and upland grazing

Studies in areas of upland grazing and elsewhere where meteorological and soil factors limit pasture improvement are particularly vital. Indeed, Munro and Davies (1973) note, for example, that the climate of hills in Great Britain is one of the most severe and highly variable encountered in pasture improvement in the world. Temperature lapse rates are particularly sharp, causing marked reduction in the length and intensity of the growing season, compared with the surrounding lowlands. Frost damage is a major factor contributing to both yield and botanical deterioration of improved pastures. Soil fertility and drainage limitations are also of great importance; plant factors can modify the severity of these climates and soil limitations and programmes of breeding grasses for increased winter hardiness are in progress in the United Kingdom

With increased improvement of rough hill grazings there is scope for the use of special-purpose crops for conservation, lamb fattening and stock wintering (Munro, 1981). The key to a better nutrition cycle for the grazing animal lies in pasture improvement.

C.2.3 Examples of the use of strategic assessments of pasture quality

C.2.3.1. Dairying

Weather-based predictions of dairy production one to two months ahead are provided by the New Zealand Meteorological Service on a regular basis to the New Zealand Dairy Board (Maunder, 1977). Consecutive daily rainfall amounts from a network of stations provide an estimate of soil moisture deficit and hence of the potential for pasture growth. Such assessments, together with climatological and synoptic forecasts of probable conditions for the rest of the month, are weighted by the dairy cow distribution and compared with previous seasons. A prediction of dairy production is then given in terms of a percentage change from the corresponding period in the previous season (Table C.5). The financial value of the prediction is claimed to be considerable.

Smith (1968) used the idea that June rainfall influences hay quality to deduce a forecasting equation for dairy cow milk yields in England and Wales. By the end of June, accurate nine-month forecasts seemed possible using June rainfall and the April-June milk production data. Forecasts for 12 months ahead at the end of March used November-March milk production and March soil temperatures (indicating spring grass quality) with only slightly less accuracy.

C.2.3.2 Sheep - wool production

Soil moisture data are also used (Rich, 1977) to assess grass availability for feed and hence, through sheep liveweight, the wool-clip production of New Zealand.

C.2.4 Example of tactical forecasts of pasture quality

An operational programme illustrating the tactical use of weather forecasts in grassland management is reported by Roberts (personal communication, 1984). Samples of grass from around Wales (United Kingdom) are assessed for digestibility ("D" value), by nutrition chemists and agronomists of the Advisory Service of the Ministry of Agriculture, Fisheries and Food (MAFF). "D" values change rapidly with temperature, rainfall and insolation (Walters, 1976). Advice on pasture quality based on sample analysis will inevitably follow several days after the sample cuts. "D" values are issued based on an analysis of recent weather and a weather forecast for three days ahead by Cardiff Weather Centre (S. Wales, United Kingdom). The MAFF issues advice on the likely trends in "D" values in the light of *in vitro* values and weather trends since sampling. Tactical decisions on programmes of cutting for hay or silage can then be made by individual farmers. Meteorological forecasts will be vital here and Barrie (1978) presents a nomogram which could be used by forecasters to define "drying days".

C.3 Nutritional requirements

Logically, energy balance requirements and hence energy (feed) intake should be altered tactically in response to the climatic environment, since there is clearly a production penalty if the energy intake of animals is diverted to simply keeping them warm (Ames, 1986) (Appendix B).

Reduced feed intake in high temperature environments (both natural and controlled (e.g. housed)) commonly requires attention to be given not only to the energy content of the feed but also to its vitamin and mineral content. If these latter are inadequate, then the experience of the intensive poultry industry, for example, is that production suffers. Reduced feed intake in cold or arid environments can likewise be a scurce of deficiency disorders. Several schemes have been proposed to accomplish energy adjustments for sheep exposed to cold (Lofgren, 1974; Filmer and Curren, 1977).

C.3.1 Nutritional deficiency disorders

Disorders such as swayback, hypomagnesaemia and twin lamb disease have been the subject of successful forecasting techniques (Smith and Ollerenshaw, 1967).

C.3.1.1 Swayback

Swayback is a nervous disorder of new-born lambs characterized by inco-ordination of movement. It is associated with copper deficiency in the pregnant ewe and, in the United Kingdom, is generally accepted to be more prevalent in springs following mild, open winters. The number of days of snow cover provides an index of the amount of supplementary food given to in-lamb ewes, with copper-inhibiting swayback (although the ingestion of soil also plays a role in inhibiting copper metabolism) (Figure C.6). Timely forecasts are available from the Ministry of Agriculture, Fisheries and Food at the end of January, although the incidence can be modified by February snow.

As with other diseases, the forecasts can be confounded by farmers continuing preventive measures in years following a high incidence!

C.3.1.2 Hypomagnesaemia

A flush of grass growth in early spring in the United Kingdom following unseasonally warm weather can result in dramatic ewe fatalities from hypomagnesaemia (Smith, 1975). Since such a flush can be exploited shortly before tupping to encourage the conception of twin lambs, the operational value of forecasts of temperature and rainfall a week ahead are clear.

C.3.1.3 Twin lamb disease

There are incidences where, although weather-animal health relationships have been established, the forecast of disease requires longer-range weather forecasts than are currently available. Twin lamb disease, (a nutritional disease in sheep carrying twins) is one such example. Smith and Ollerenshaw (1967) describe a disease index based on the product of cold stress (measured as degree-days below 0°C) and excess winter rain over 400 mm - both summed over the winter period. The former factor is an indicator of poor grass growth, the latter of physiological stress.

C.3.1.4 Graphical monitoring of climate

The progress of below-average temperatures and above-average rainfall can be monitored in a graphical form as the winter progresses (Figure C.7), allowing a satisfactory estimate of the level of twin lamb disease to be made in the United Kingdom by the end of December (Ollerenshaw, 1980). (The technique can be applied to parasitic diseases.)

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C.4 Fungal disease

The fungus *Sporesdesium bakerii* causes facial eczema in sheep. The disease is a particular problem in New Zealand and was one of the first animal health problems to be accurately forecast by meteorological information (Filmer, 1957). The fungus develops on ryegrasses and ingestion results in liver damage often accompanied by facial skin lesions. The disease occurs in autumns following hot, dry summers in which grass dries off or makes little growth. The Department of Agriculture accordingly broadcasts warnings to districts prone to the disease, when the past week's temperature has been above average.

The proportion of cast wool in half-bred and fine wools in Great Britain was found by Smith and Austwick (1975) to be correlated with the number of occurrences of heavy rain during the two years previous to shearing. The heavy rain is thought, initially, to encourage skin infection through the actinomycete *Dermatophilus cangolensis*, and, in the second year, the spread from carrier sheep. With the aid of analysis of the critical rainfall conditions (> 5 mm of rain in 15 minutes), forecasts of acceptable accuracy of the forthcoming wool clip should be possible some six months before shearing and grading. Rainfall data based on radar measurements (Browning, 1982) could prove ideal for such forecasts based on rainfall intensity statistics.

C.5 Bacterial disease

Temperature is a prime factor in the multiplication of bacteria which are classified according to the temperature bands within which they replicate (*Guide to Agricultural Meteorological Practices* (WMO-No. 134) - chapter on weather and animal health under preparation).

Botulism in water fowl is caused by the ingestion of food containing a toxin produced by an anaerobic bacterium. The disease has been identified in many parts of the world. Smith (1979) derived an index for the United Kingdom reflecting the influence of temperature on replication and evaporation (lowered water levels reveal the bacterial habitat). A forecast of the disease, however, requires a forecast of the occurrences of high temperatures and dry days in the month ahead and such detail is, as yet, beyond current techniques. However, as a case-study leading up to a quantitative understanding of the role of environmental variables in a weather-driven disorder, the work is instructive.

*

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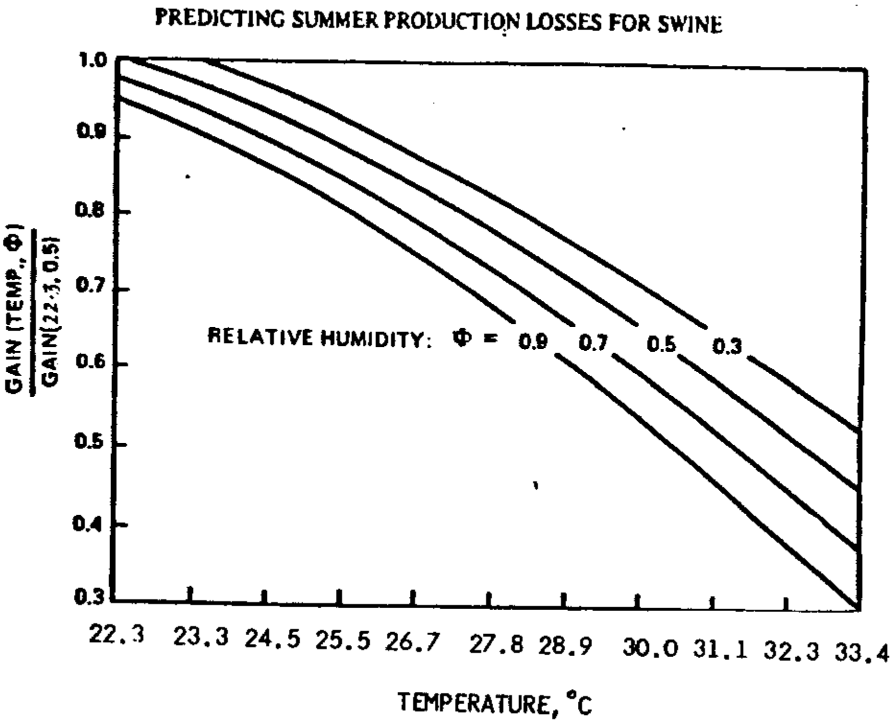

Figure C.1(a) - Weight gains in swine at a constant relative humidity of 50 per cent as a function of air temperature and liveweight (Morrison et al., 1970)

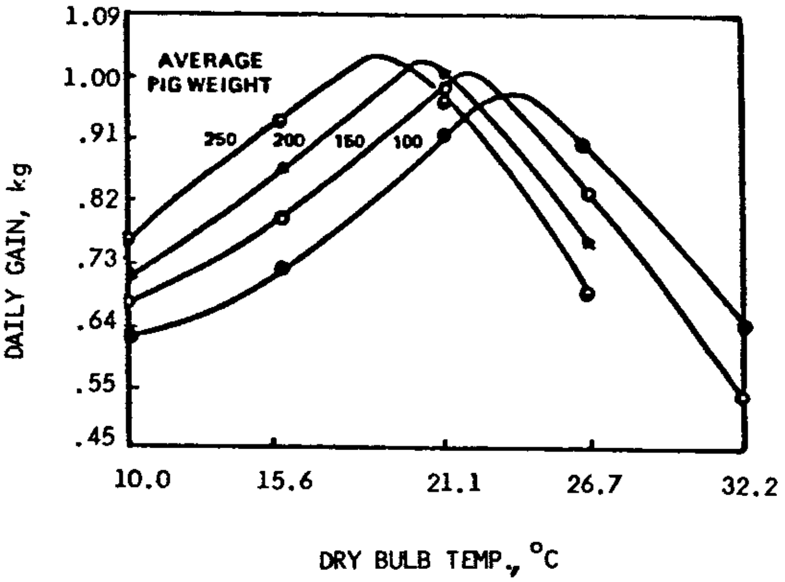

Figure C.1(b) - Ratio of weight gain for 68 kg pigs at a given relative humidity and temperature to that at 22.3 C and 50 per cent humidity (Φ = 0.5)

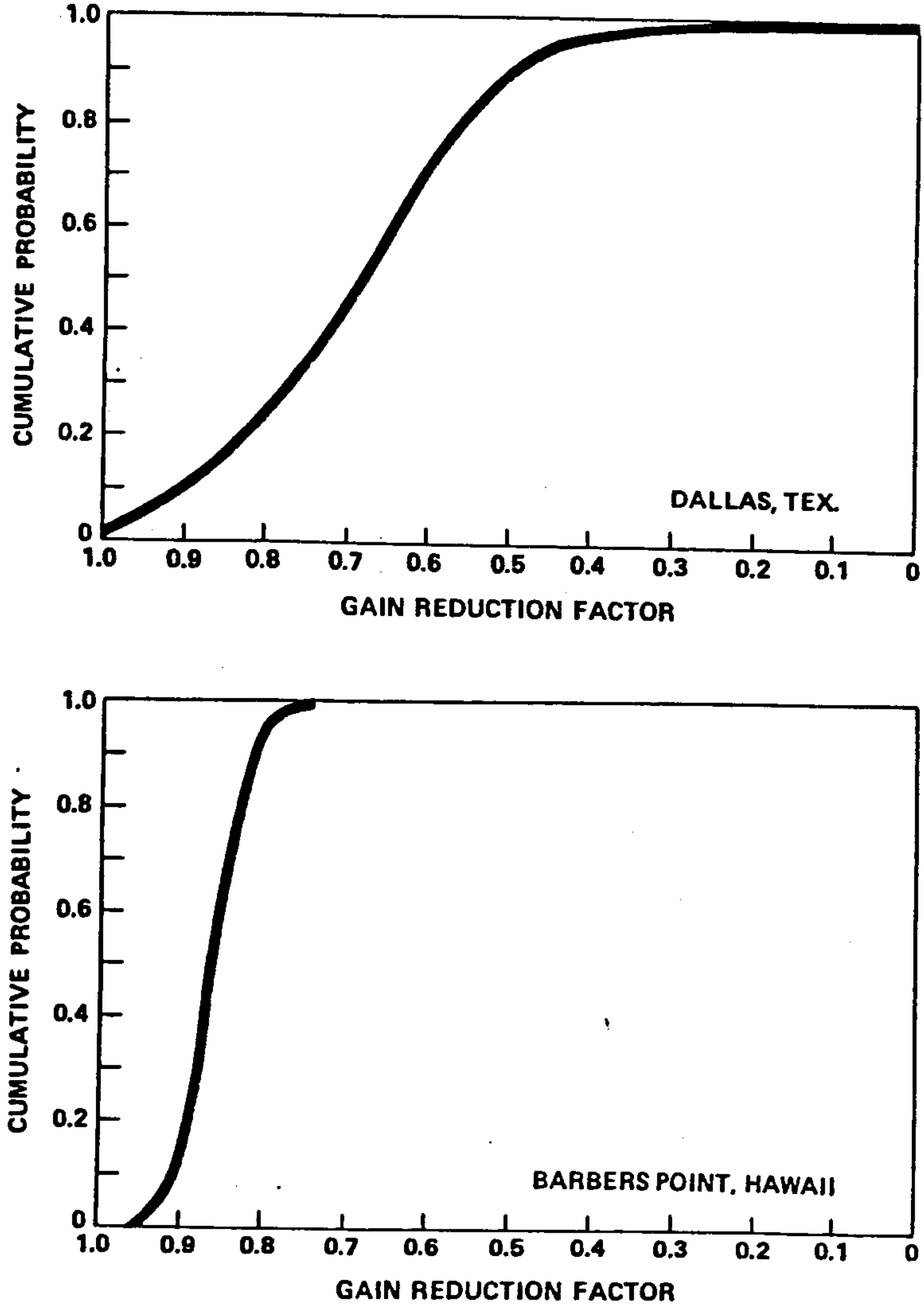

Figure C.1(c) - The cumulative probability (the probability that the gain reduction factor will be any specified value or larger) for two USA locations

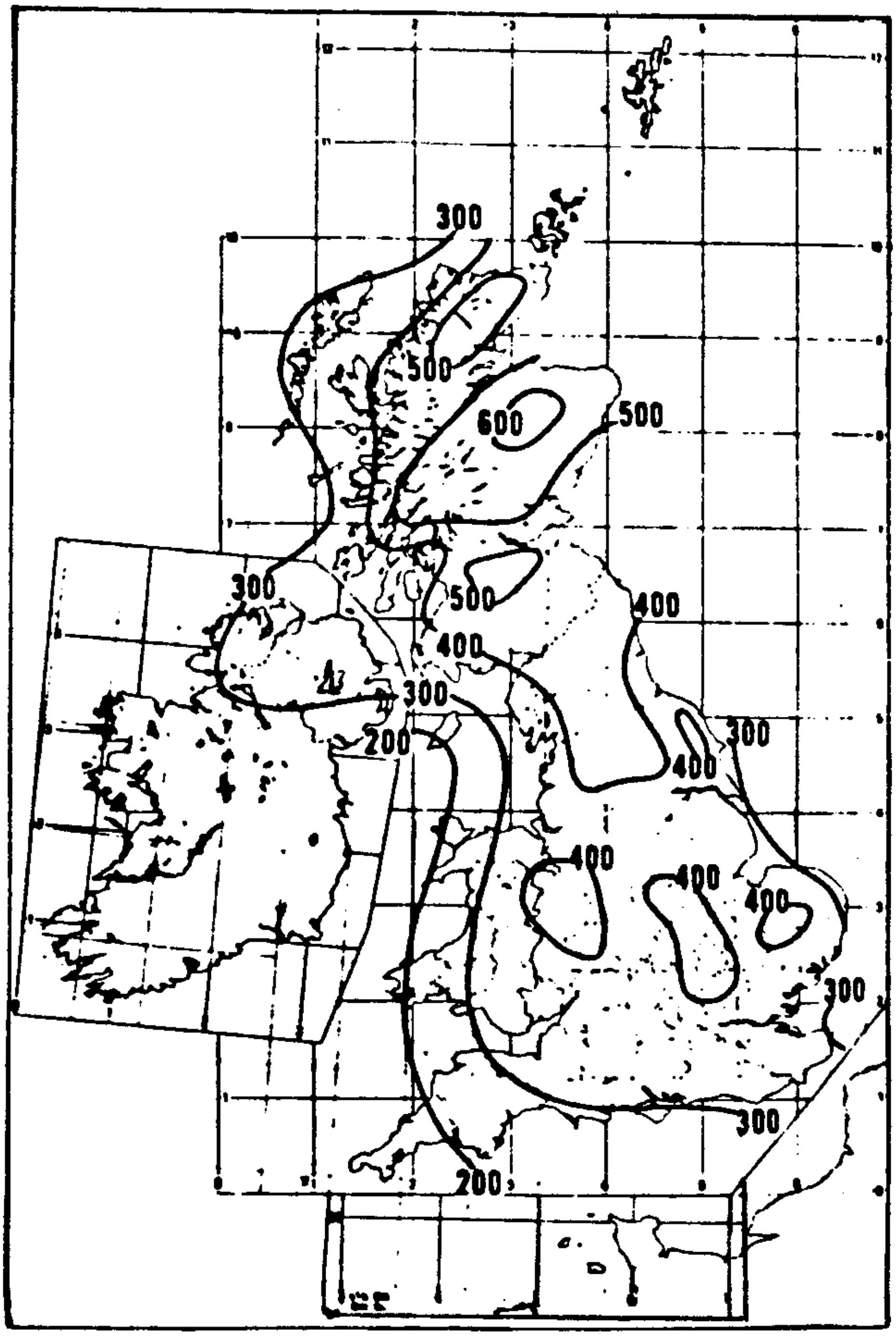

Figure C.2 – Average accumulated temperature in day-degree Celsius below 5.6°C in the United Kingdom (at mean county height below 300 m) indicative of the degree of cold stress on steers (Smith, 1974). (5.6°C is close to the lower critical temperature for this class of livestock.)

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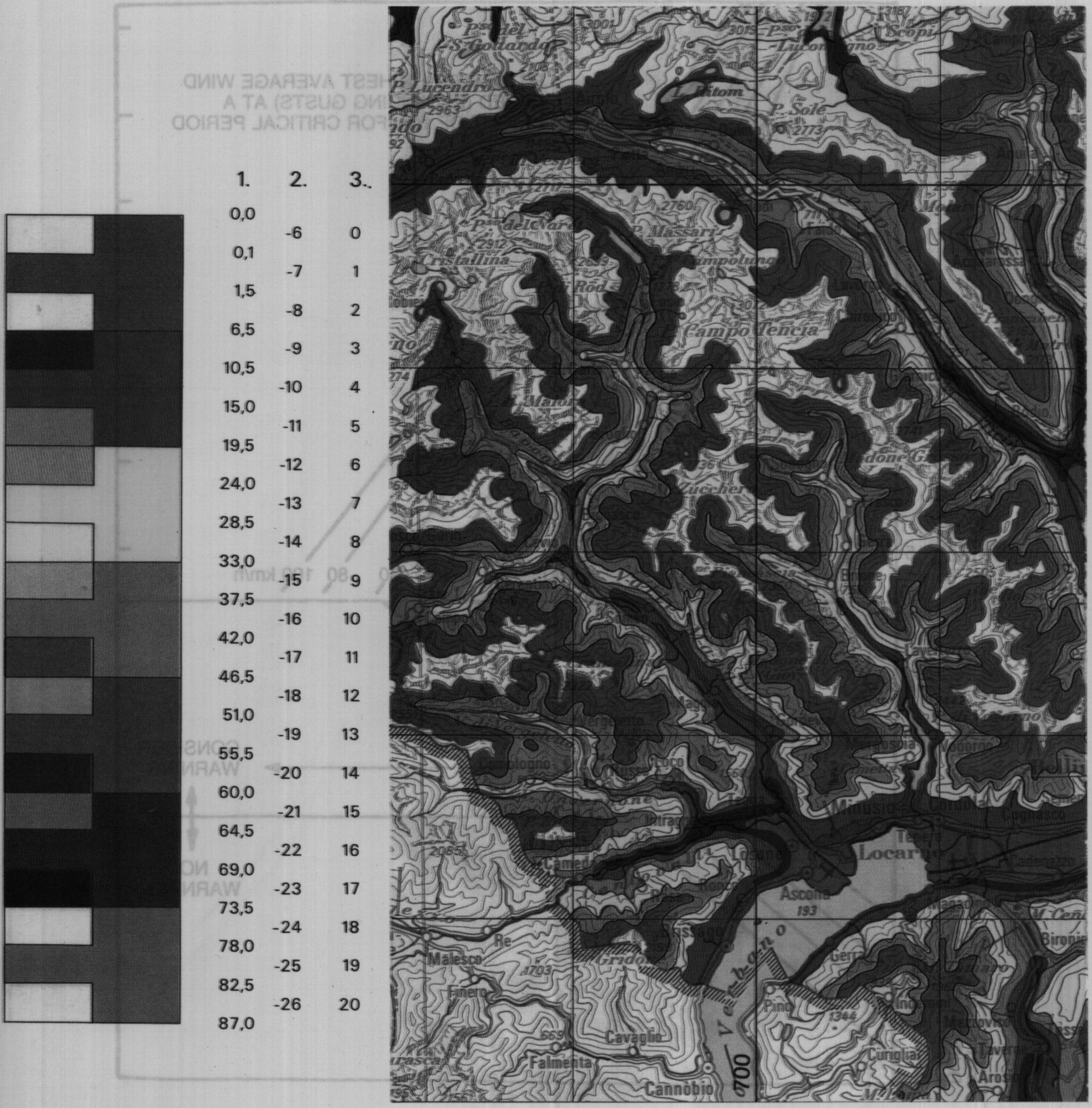


Figure C.3 – Maps of index of "coldness" for part of Switzerland (Primault, 1982) (mean of 1931-1960)
1: Number of days of ice. 2: Index of coldness. 3: Class

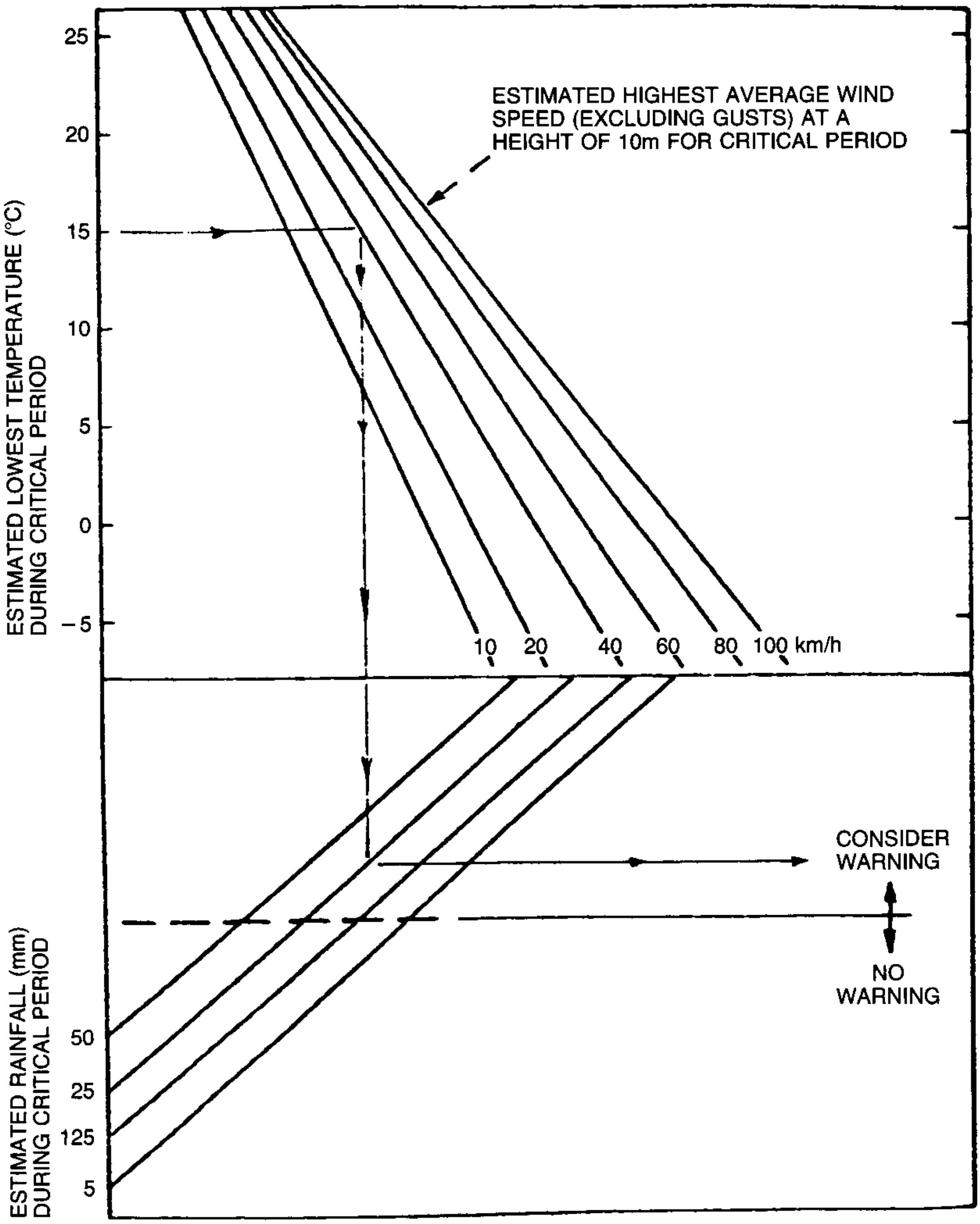


Figure C.4 – Australian Weather Service nomogram for warning of hypothermia in sheep

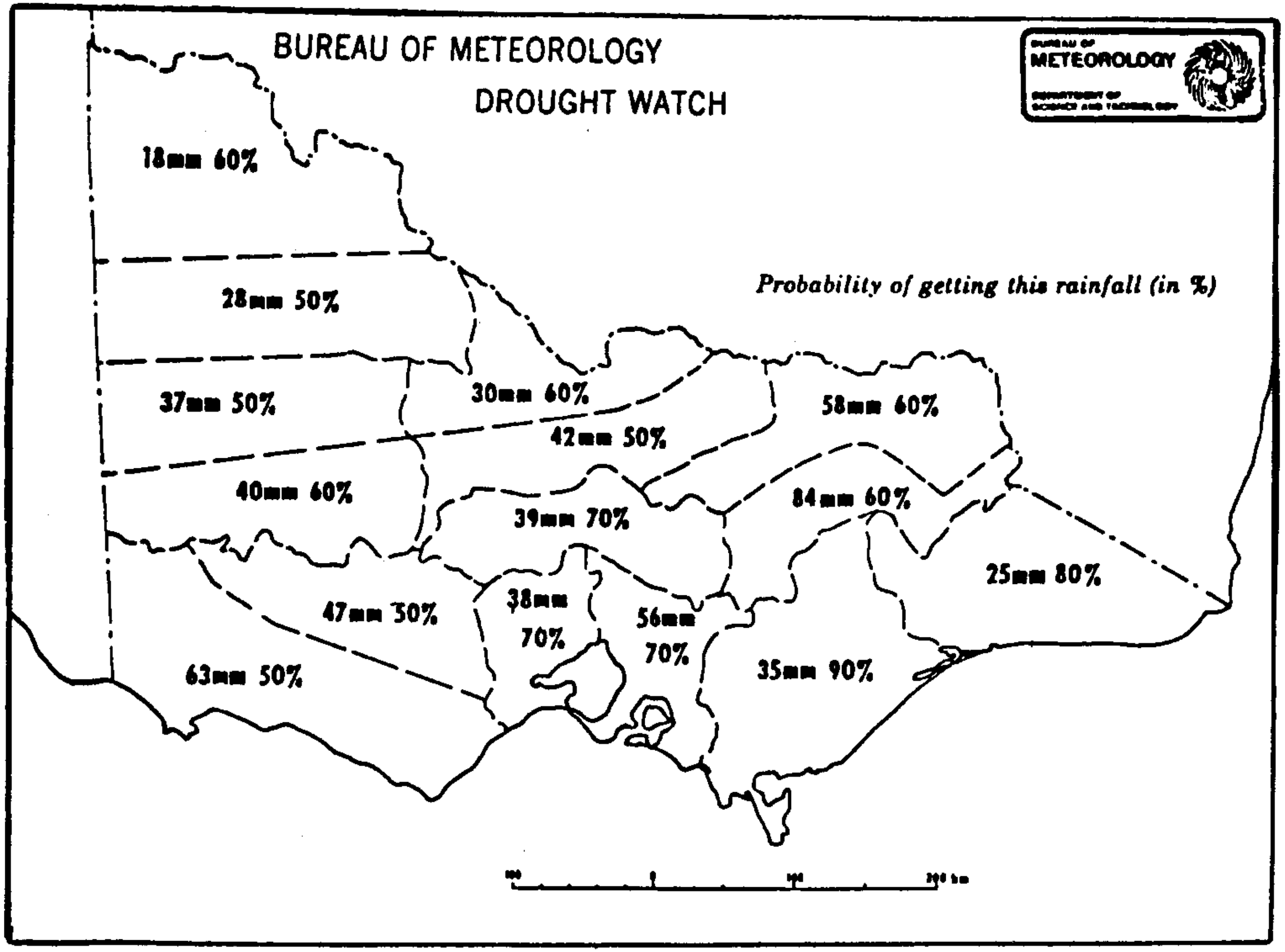


Figure C.5 - District average rainfall needed in June to avoid serious deficiency (Australian Bureau of Meteorology drought watch)

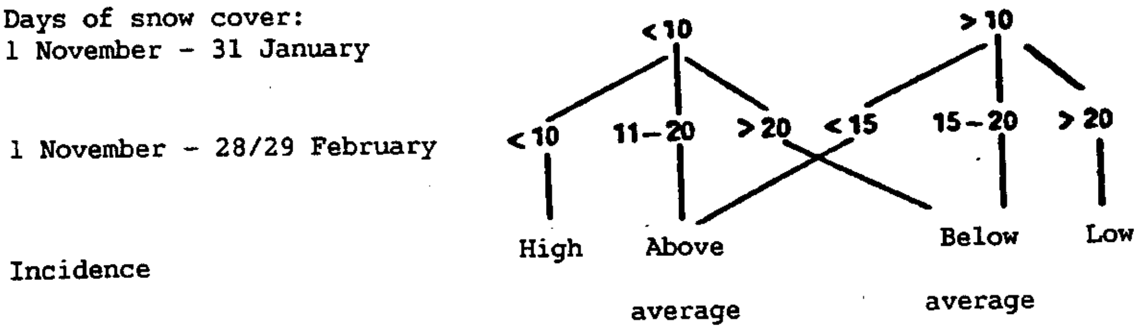
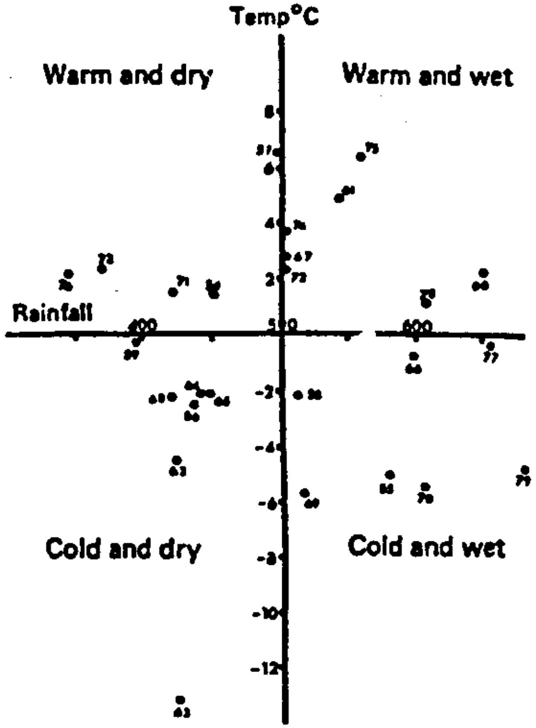
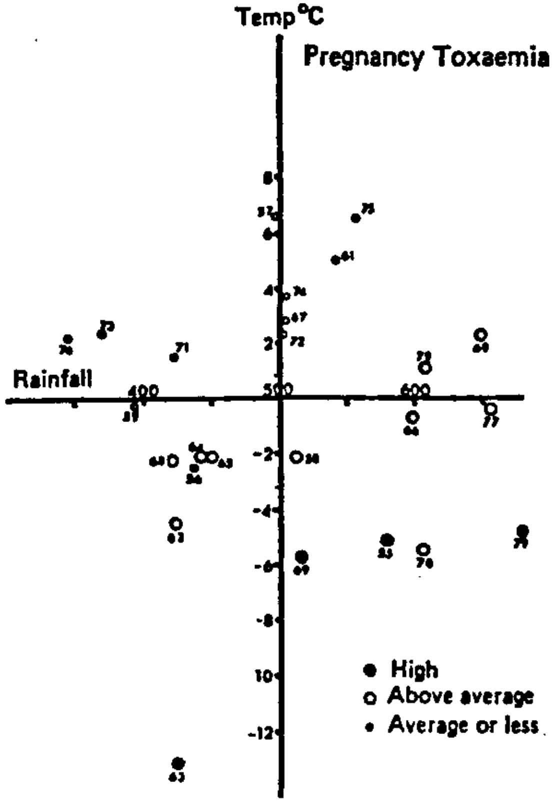


Figure C.6 – Incidence of swayback in lambs related to the number of days of snow cover. A guidance forecast for spring is available in the United Kingdom at the beginning of February. Subsequent snowfall can modify the forecast

Month	November	December	January	February	March	Total
Temperature °C	+1·7	−0·3	−3·0	−2·2	−1·0	−4·8
Rainfall %	45	230	100	104	191	670



Scatter diagram classifying the winter weather over England and Wales from 1954–1979 according to table above



The level of pregnancy toxaemia in relation to winter weather

Figure C.7 – Twin lamb disease – assessment by monitoring the progress of winter in terms of departures of rainfall and temperatures from the average (Ollerenshaw, 1980)

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APPENDIX C

TABLE C.1

Hours a stress index of 85 is exceeded per year with and without evaporative cooling for swine (Fehr et al., 1982)

Location	Hours exceeding a stress index of 85		Percent reduction
	Without evaporative cooling	With evaporative cooling	
Jackson, MS	1 519	265	82.6
Raleigh, NC	930	105	88.7
Jackson, FL	1 774	265	85.1
Lexington, KY	1 276	308	75.9
Des Moines, IA	593	70	88.2

TABLE C.2

(from Cochrane, 1984)

(a) Tolerable environmental temperatures for broiler poultry at different rates of water use

Assuming that the bird's body temperature is constant at 41°C and that the lower (sustainable) rates of water use are applicable, then tolerable environment temperatures in the house, T_e, at different rates of water use are:

Bird weight:		1.5 kg		2.0 kg	
W g d^{-1}	E J s^{-1}	H_s J s^{-1}	T_e °C	H_s J s^{-1}	T_e °C
50	1.4	8.6	25.2	11.1	22.9
100	2.8	7.2	27.7	9.7	25.2
150	4.2	5.8	30.3	8.3	27.5

(These figures assume that the whole of the bird's surface area is exposed to ventilating air and is effective in heat dissipation.)

(b) Short-period environmental temperatures that are tolerable

If body temperature can rise, under increasing stress, to 45-46°C before death occurs, then the tolerance temperatures may be raised by up to 5°C. If, at the same time, water use increases, the estimated environment temperatures which may be tolerated for shorter periods are (body temperature 45°C):

Weight:		1.5 kg		2.0 kg	
W	E	1.0A	0.5A	1.0A	0.5A
200	5.6	37	29	34	22
300	8.4	42	39	38	32
350	9.8	45	44	41	36

Key: E = evaporative cooling; H_s = sensible heat transfer; T_e = environmental temperature; W = water use per bird (g d^{-1}); A = surface area per bird

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Table C.2 (cont.)

(c) Example of broiler losses due to heat stress

During a 13-day spell (9-21 July), more than 18 500 birds aged 37-49 died. This loss represented over 13 per cent stock in four houses.

Date (July)	T_{max}°C	Number dead
8	27.6	-
9	27.1	828
10	26.1	380
11	30.1	204
12	30.1	14 721*
13	31.2	200
14	28.1	1 133
15	29.7	359
16	30.3	112
17	25.4	194
18	25.7	305
19	25.0	82
20	21.5	53
21	24.0	66

* The high number of deaths attributed to 12 July is also the result of deaths occurring during the evening of 11 July. The tendency for fewer deaths after 12 July must be due, in part, to the steady reduction in stocking density as dead birds were removed; the initial density was 19.1 birds per square metre, falling to 16.9 birds per square metre by 13 July.

(d) Influence of crowding and clustering

If, due to crowding or clustering, the bird's effective surface area, A, is reduced by, say 25 or 50 per cent, the tolerance temperatures at which body temperature can be maintained become:

Bird weight:	1.5 kg		2.0 kg	
W	0.75A	0.5A	0.75A	0.5A
		T_e		
50	19.9	9.3	16.9	4.9
100	23.3	14.5	19.9	9.4
150	26.7	19.6	23.0	14.0

Under conditions of local overcrowding, the bird cannot maintain its body temperature - even at a high rate of water use - at house temperatues as low as 15-20°C.

Key: A = surface area per bird; W = water use per bird (g d^{-1})

Table C.2 (cont.)

(e) Influence of ventilation on tolerable environmental temperatures

(at body temperature 45°C and maximum ventilation rate of $28\ m^3\ s^{-1}$ per 1 000 birds)

Weight:		1.5 kg		2.0 kg	
W	E	1.0A	0.5A	1.0A	0.5A
			T_e		
150	4.2	32	22	29	16
250	7.0	39	33	34	25
350	9.8	45	44	40	35

(f) Effect of crowding or clustering with ventilation

(body temperature 45°C)

If, because of clustering or other reasons, effective ventilation is reduced by 50 per cent, these tolerance air temperatures become:

Weight:	1.5 kg		2.0 kg	
W	1.0A	0.5A	1.0A	0.5A
		T_e		
150	31	20	27	14
250	38	32	33	24
350	45	44	39	34

Key: E = evaporative cooling; W = water use per bird ($g\ d^{-1}$); T_e = environmental temperature; A = surface area per bird

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TABLE C.3

Accumulation of day-degrees Celsius below various bases for a typical sample of years, for a site in East Anglia (United Kingdom) (Smith, 1974)

Base/year	1	2	3	4	5	6	7	8	9	10
-0.7°C	8	12	22	30	41	46	53	70	87	129
1.3°C	18	42	55	66	83	95	112	131	170	235
3.3°C	62	91	124	140	162	190	219	250	290	400
5.3°C	131	172	219	253	285	322	345	400	448	555
7.3°C	240	300	360	400	449	492	541	600	745	800
9.3°C	393	494	568	655	668	720	772	832	910	1 070
11.3°C	595	710	790	865	920	985	1 030	1 100	1 190	1 415
13.3°C	850	1 010	1 080	1 140	1 220	1 280	1 340	1 400	1 500	1 650

TABLE C.4

Decision matrix - wintering of young beef cattle (Smith, 1974)

	Season	1	2	3	4	5	6	7	8	9	10	
	Probability of season occurring	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	Average outcome
Management options	No housing, *ad libitum* hay	$O_{1,1}$	$O_{1,2}$	$O_{1,3}$	$O_{1,4}$	$O_{1,5}$	$O_{1,6}$	$O_{1,7}$	$O_{1,8}$	$O_{1,9}$	$O_{1,10}$	$(1/10)\sum_{i=1}^{i=10} O_{1,i}$
	No housing, *ad libitum* hay, supplementary barley	$O_{2,1}$	-	-	-	-	$O_{2,6}$	-	-	-	$O_{2,10}$	$(1/10)\sum_{i=1}^{i=10} O_{2,i}$
	Housing *ad libitum* hay	$O_{3,1}$	-	-	-	-	$O_{3,6}$	-	-	-	$O_{3,10}$	$(1/10)\sum_{i=1}^{i=10} O_{3,i}$
	Housing, *ad libitum* hay, supplementary barley	$O_{4,1}$	-	-	-	-	$O_{4,6}$	-	-	-	$O_{4,10}$	$(1/10)\sum_{i=1}^{i=10} O_{4,i}$

TABLE C.5

The value* of predicted and actual milk fat production differences between March 1972 and March 1973 (Maunder, 1977)

Region	Predicted difference** ($m)	Actual difference ($m)
North Auckland	-0.9	-3.1
South Auckland	-2.8	-4.0
Bay of Plenty	-0.5	-0.5
Taranaki	-3.8	-3.1
Hawkes Bay/Gisborne	-0.2	-0.9
Wellington/Manawatu/ Wairarapa	-0.5	-0.2
South Island	-0.5	-0.2
New Zealand	-11.3	-13.0

* Based on the March 1972 volume of production and a value of $2.50/kg which is the value if milk fat is converted into cheese and exported (prices as of mid-1977).

** The difference between March 1973 and March 1972

APPENDIX D

AIRBORNE INFECTION

The topics covered in this appendix are introduced in Chapter 1, sections 1.3 and 1.5.

D.1 Dispersion and infection within livestock housing

The control of the housing environment involves more than just attention to virus and gaseous emissions (Smith, 1972). This dispersion of the contaminants, and therefore their concentration, will be influenced by internal air movements which will depend on:

(a) External meteorological conditions (and contrasts between internal and external environments) which will influence ventilation (air change) rates and internal airflow patterns (Figure B.3). Wind and temperature are clearly important (Muller *et al.*, 1978; Golosov and Sadovnikov, 1978; Bruce, 1978 and 1981);

(b) The "stack effect" i.e. ventilation induced by temperature contrasts (Carpenter, 1981) (Appendix B);

(c) The capacity or rating of heating and ventilation systems (Clark, 1981);

(d) Internal geometry and fittings (Figure B.5) (Randall, 1981);

(e) Livestock stocking density and movement (Randall, 1975).

D.1.1 Air quality - the role of ventilation and relative humidity

Basic influences on air hygiene will be ventilation rate, the proportion of virus-bearing air recycled in the vicinity of livestock and the influence of the environment on virus viability. For the first factors, stock density has a direct bearing on the volume of the house or the volume of air within the house allocated to each animal. This, in turn, has a bearing on the recycling rate of air breathed by one animal that is subsequently inhaled by another. In air-hygiene terms a trade-off is possible between house air-change rate and stock density (Smith, 1983).

Concerning the question of virus viability, Webster (1981) and others (Donaldson and Ferrier, 1976; Donaldson, 1978) report on some of the profound influences of relative humidity and temperature. These are summarized in Table D.1. It is interesting to note, however, that recent calf house studies by Wathes *et al.* (1983) and Webster (1984) indicate that air hygiene, measured by virus death rate, is principally determined by stocking rate and relative humidity, ventilation rate being less important (Figure D.1). Other studies are needed to support the implication that ventilation rate is only important to air quality if linked to a system to maintain low relative humidity.

D.1.2 Prediction and control of airborne infection

Only a clearer understanding of the dynamics of population changes in pathogenic organisms following weather changes offers the possibility of analysing how weather and other environmental factors contribute to the genesis of an epidemic (Pritchard, 1980; Roe, 1982) (Chapter 1, section 1.3.3). Certain successes, however, have been achieved in studies on the spread of secondary infection. By looking at dosage rates, Smith (1983), for example, illustrated that host-virus contact is not materially altered by whether livestock are housed or not; certainly physical separation of housed stock on the scale permitted by individual holdings (several hundred metres) is not likely to be sufficient to avoid significant airborne contact (Tables D.2 (a) and (b)) (Mueller et al., 1978; Hosker, 1980).

D.1.2.1. Foot-and-mouth disease (FMD)

Meteorological information has been successful in explaining many aspects of the spread of foot-and-mouth disease. Historically, though, this success followed from a study of the spatial and temporal sequences of outbreaks of Newcastle Disease (Fowl Pest) in central England in the late 1960s. Smith (1964) explored the possibility that infectious particles in the air, emitted from intensively stocked broiler houses where the birds were infected, would be carried downwind in the coherent plume. The location of secondary outbreaks of Newcastle Disease was essentially explained by the passage of the plume over other houses downwind. The timing of secondary outbreaks was linked with this occurrence, after allowance was made for an incubation period of three to four days for the virus in the newly infected birds. Following the 1967 outbreak of foot-and-mouth disease in southern England, Smith and Hugh-Jones (1969) extended the hypothesis to take account of adequately high relative humidity to maintain virus viability and, using estimated source strengths, satisfactorily explained the observed distribution of secondary outbreaks using wind-sector analysis (Figure D.2 (a) and (b)). (A similar hypothesis has been proposed by Primault (1974) from FMD epizootics in Switzerland.)

Subsequently, these ideas have been incorporated into a numerical diffusion model (Blackall and Gloster, 1981) which permits estimates to be made of virus dosages out to at least 10 km, inputs being source strength, wind characteristics, atmospheric stability and topography. This Gaussian plume numerical dispersion model allows estimates to be made (at 1 km steps along a bearing appropriate to a reciprocal wind direction) of the virus concentration in the air in terms of "infection units". Thus, by relating such data to veterinary experience, the area of daily risk can be defined as any position exceeding a daily dosage of 0.1 infection units (IU). Figure D.3 and Table D.3 illustrate the calculated model output for two days, the 1.0 IU isopleths only being drawn on the figure for the sake of clarity.

The model has been used operationally in the March 1981 United Kingdom foot-and-mouth disease outbreaks in Jersey and the Isle of Wight (Figure D.4) (Donaldson et al., 1982). Here, virus transport of several hundreds of kilometres over the sea from an intense continental source, was favoured by a stable airstream and moderate winds (Michelson, 1975; Gloster, 1982) (Figures D.5 (a) and (b)). The resulting swift diagnosis, and application of control measures by the Ministry of Agriculture, Fisheries and Food apparently reduced the direct cost of this outbreak to a few hundred thousand pounds, compared with the tens of millions direct cost of the

1967/1968 epidemics, when half a million animals were slaughtered. Gloster et al. (1982) describe semi-quantitative analyses of 23 cases of exposure to virus where the original outbreaks were separated from later outbreaks by a sea passage.

Powell (1984) reports Australian investigations into likely areas where the disease would prosper. The investigation maps areas where virus viability is thought to be encouraged because of fairly frequent high relative humidity in association with an absence of insolation.

D.1.2.2 Newcastle disease

There are few quantitative data as yet on the emission of Newcastle disease virus (ND) by infected poultry, making the quantitative prediction of the airborne spread more difficult (Gloster, 1983). The direction can, however, be estimated.

Since little is known about the relation between infection and the number, age and health of various classes of poultry, it is not yet possible to estimate whether a large unit exposed to virus for a short period may be more at risk than a smaller one exposed for many hours. The following questions need to be answered about ND before predictions as accurate as those for FMD can be made:

(a) How much virus - as a function of strain, disease stage and age of poultry - is released into the atmosphere?

(b) Once airborne, what governs virus viability?

(c) What is the minimum quantity of virus to cause infection?

(d) What effect does stocking density have on the likelihood of subsequent infection?

D.1.2.3 Aujezsky's and other diseases

Aujeszky's disease (Gloster et al., 1984), African swine fever virus (Wilkinson et al., 1977) and Marek's disease in poultry (Glezer and Tarasenko, 1977) are other diseases in which airborne infection is considered to play a major role (see Table 1.3).

D.1.3 Insect vectors

Airborne transmission of disease by insect vectors has been suggested as the likely vehicle of African horse sickness (Sellers et al., 1977; Sellers, 1978) and Rift Valley fever (Pedgley, 1982). Models based on those for particle diffusion offer the possibility of quantitative operational estimates of disease risk in areas outside endemic areas (although other factors - such as wind convergence - may dominate).

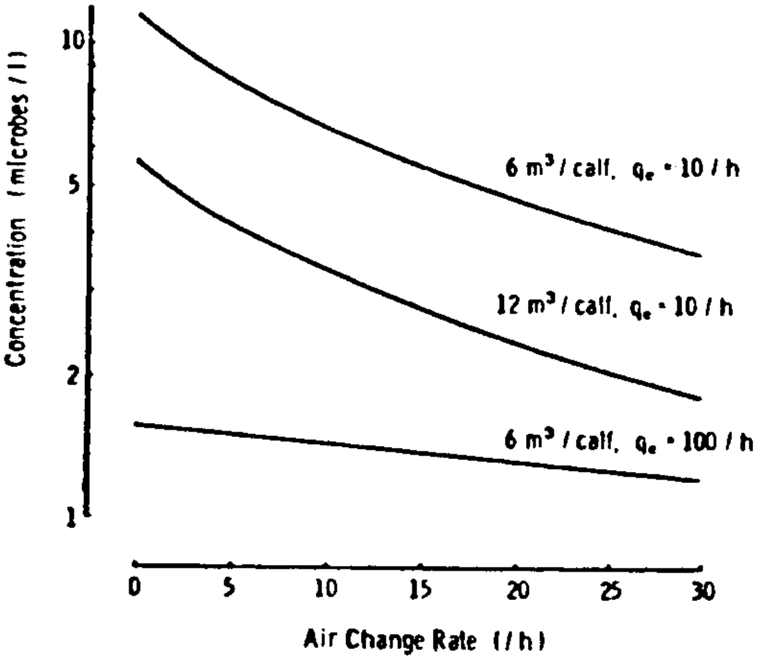

Figure D.1 - Model relationship between ventilation rate, stocking density and concentration of airborne microbes (Qe = rate of clearance by all routes, excluding ventilation) (Wathes et al., 1983)

START INDEX

1. In the initial stage of an outbreak of foot-and-mouth disease, a simple analysis of the weather preceding the occurrence of the primary outbreak is urgently required. The detailed advice now called for is intended to provide a back-up to the computerized dispersion programmes.

2. The information available from the veterinary authorities will be:

(a) Site of primary outbreak;

(b) Period over which virus is thought to have been emitted from this source (a matter of days, generally 2 to 7).

The advice required concerns the spatial distribution of winds during the significant period.

Method

3. Use a double foolscap sheet of paper with columns headed, 1,2,3 ...36 and calm (for surface wind direction in 10° sectors centred on 10°, 20°, 30° .....360°). From the hourly observations of a nearby observing station, (supplemented or replaced where necessary by reference to hourly charts) make an entry in the appropriate surface wind direction column. Treat force 1 winds as calm.

4. If the emission period is given as a range of days or hours, take the longest period.

5. Two types of sector can be discerned from the analysis:

- Sectors from which winds have been observed;
- Sectors enclosing directions from which no winds have blown.

To allow for the fact that winds are reported to the nearest 10°, extend the observed wind sectors by 10° at both extremities. In addition, extend the observed wind sectors by 30° of voer to allow for wind change with height. Single 10° sectors should not be specified separately but added to the adjacent sector of greater importance.

6. The advice is required in terms of bearing from the source, so that for transmission, the reciprocals of the directions obtained from the analysis should be given. To avoid possible confusion, sector limits should be reported in clockwise order; if any sector includes one or more of the four cardinal points, name one of them e.g. "040° to 210° through south". The message should be passed to the required address by telephone in the following manner:

- RED SECTOR (ie. sector into which virus would be transported) 360° - 110° through east.

To this should be added:

- The most common wind directon for each RED SECTOR;
- The number of hours of calm winds.

Figure D.2(a) - Preparation of foot-and-mouth disease sector diagram (Public Services Handbook, United Kingdom Meteorological Office)

Examples showing preparation of sector diagram

(1) Yorkshire outbreak - October 1960 (actual)

Information received: Outbreak at 18h30 on 1 October 1960 at Grid Ref SE 353 439 (7 miles NNE of Leeds) 24-48 hours old
Nearest operational station is Dishforth
Analysis to start at 18h00 on 19 September 1960 - 48 hours prior to outbreak

SURFACE WIND DIRECTION																																				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	Calm
			/	//	///	卌 ///	卌 卌 卌 卌 /	卌 卌 /	卌																											
			1	2	3	8	21	11	5																											

ADVISED ISSUED Outbreak at: SE 353 439:-

PERIOD COVERED	29.1600 to 011900 GMT
RED SECTOR	210° - 320° through west
COMMMONEST DIRECTION	260° - 21 hours; no calm

Figure D.2(b) - Foot and mouth disease warning

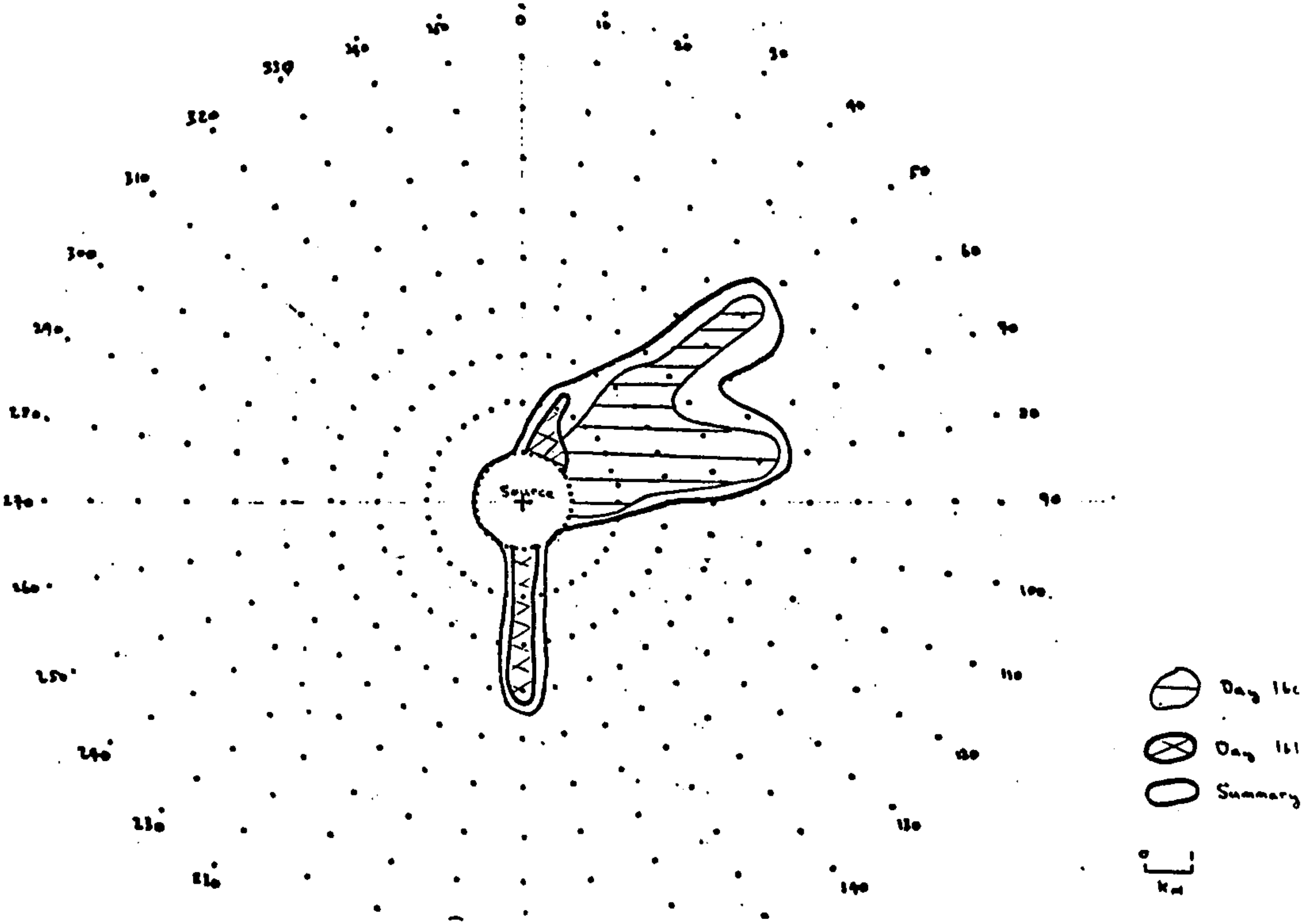

Figure D.3 - Summary diagram and final area of risk (based on 1.0 IU/day)
(Blackall and Gloster, 1981)

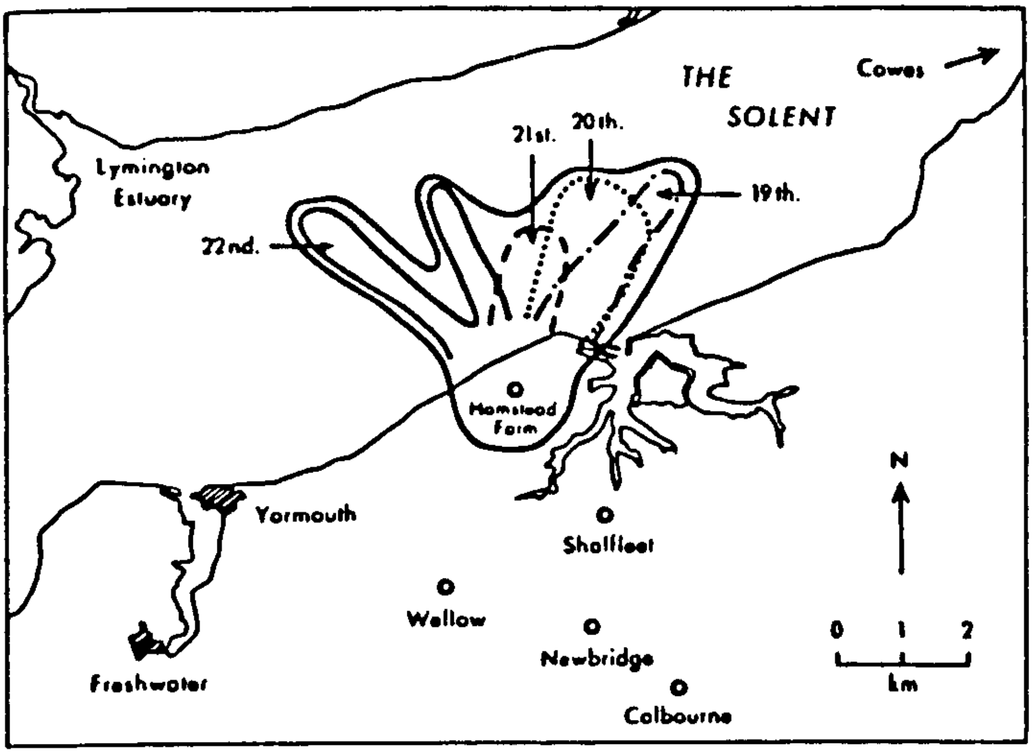

Figure D.4 - Prediction for secondary airborne spread of FMD from Hamstead Farm based on meteorological data from Hurn Airport, United Kingdom (isopleths - 0.01 IU/day) (Donaldson et al., 1982)

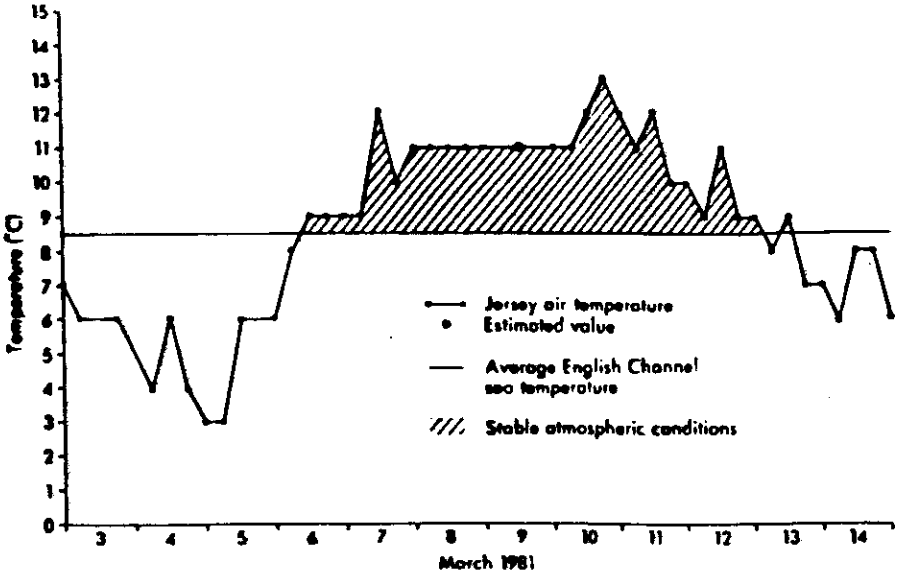

Figure D.5(a) - Atmospheric stability for spread of FMD between 3 and 14 March 1981 (Gloster, 1982)

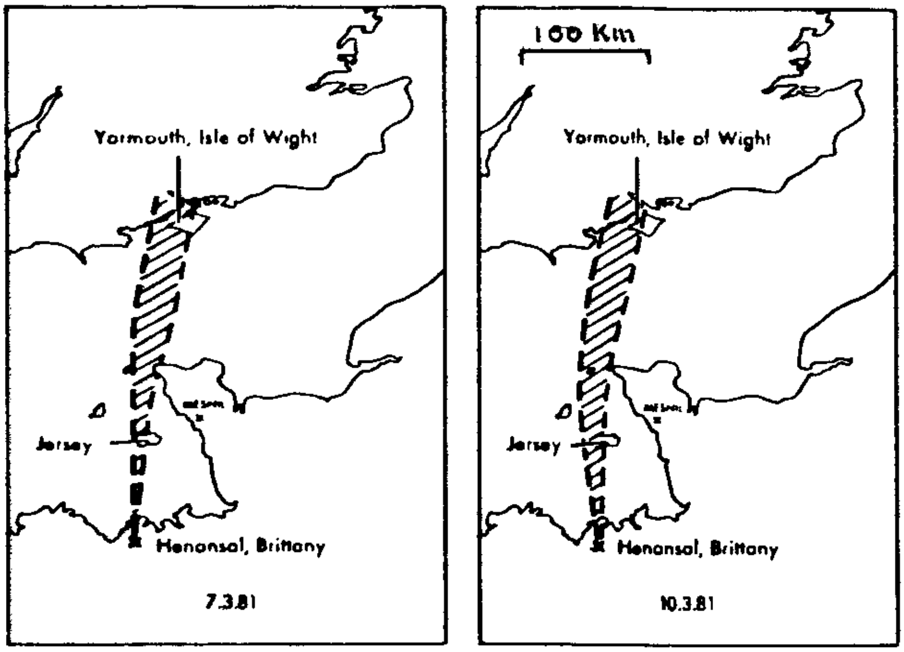

Figure D.5(b) - Air trajectories (foot-and-mouth virus) from Brittany to the United Kingdom on 7 and 10 March 1981 (Gloster, 1981)

TABLE D.1

Some effects of temperature and relative humidity on death rate of pathogens

(Donaldson, 1978

	Temperature (°C)	Relative humidity (%) 50	70	80
E. coli	Least at 15°	Slow	Rapid	Slow
Mycoplasma	10-15°	Slow	Rapid	Slow
Rhinovirus	Unaffected		Decreases	
PI 3, IBR*	Unaffected		Increases	

* PI 3 = Parainfluenza type 3
IBR = Infectious bovine rhinotracheitis

START INDEX

TABLE D.2(a)

Cattle herd size with high risk of airborne foot-and-mouth disease infection (Smith, 1983)

(Source strength 4 000 cattle or 1 pig (peak emissions); assumed wind speed 4 m s $^{-1}$)

Height of mixing layer m	Herd size* at downwind distance from source		
	10 km	50 km	100 km
100	> 30	-	-
200	> 60	> 300	-
300	> 100	-	>1 000
500	> 150		
1 000	> 300		

* Number of animals

TABLE D.2(b)

Poultry flock size with high risk of airborne Newcastle disease infection (Smith, 1983)

(Source strength 100 birds; assumed wind speed 4 m s $^{-1}$)

Height of mixing layer m	Flock size* at downwind distance from source	
	10 km	50 km
100	> 15 000	-
200	> 30 000	> 150 000
300	> 50 000	> 250 000
500	> 75 000	
1 000	> 150 000	

* Number of birds

TABLE D.3

Daily virus dosage in infection units out to 10 km at stated 10° azimuth intervals for two days of a particular exercise (Blackall and Gloster, 1981)

(a) For calendar day 160

The data for day 160 when the wind speed was below 3 kn are excluded but may be included at the meteorologist's discretion

CALENDAR DAY 160 Contours drawn up at 0.1 and 1.0

Daily dosage (all occasions) - every observation

°	1km	2km	3km	4km	5km	6km	7km	8km	9km	10km
10	1.35	0.61	0.21	0.12	0.08	0.05	0.03	0.02	0.01	0.01
20	3.45	1.37	0.93	0.76	0.65	0.59	0.54	0.50	0.47	0.44
30	1.86	0.56	0.29	0.17	0.11	0.07	0.05	0.03	0.02	0.02
40	1.17	0.43	0.24	0.16	0.12	0.10	0.03	0.07	0.06	0.05
50	1.16	0.43	0.24	0.16	0.11	0.09	0.07	0.06	0.05	0.04
60	0.63	0.23	0.12	0.03	0.06	0.04	0.03	0.03	0.02	0.02
70	0.21	0.03	0.03	0.02	0.01	0.01	0.00	0.00	0.00	0.00
80	0.03	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
90	0.00	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
100	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
110	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
120	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
130	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
140	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
150	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.0
160	0.18	0.03	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
170	2.56	0.80	0.37	0.20	0.12	0.07	0.05	0.03	0.02	0.02
180	5.53	2.34	1.42.	1.01	0.78	0.64	0.53	0.52	0.49	0.46
190	2.56	0.80	0.37	0.20	0.12	0.07	0.05	0.03	0.02	0.02
200	0.18	0.03	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
210	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.0
220	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
230	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
240	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
250	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
260	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
270	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
280	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
290	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
300	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
310	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
320	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
330	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
340	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
350	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0
360	0.07	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

TABLE D.3 (cont.)

(b) For calendar day 161

Daily dosage (all occasions)

°	0km	1km	2km	3km	4km	5km	6km	7km	8km	9km	10km
10	0.3E+06	0.01	0.00	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0
20	0.3E+06	0.25	0.05	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	0.3E+06	2.31	0.61	0.70	0.15	0.09	0.06	0.04	0.03	0.02	0.01
40	0.3E+06	8.09	2.67	1.54	0.93	0.68	0.50	0.36	0.31	0.25	0.21
50	0.3E+06	11.82	4.53	2.67	1.83	1.42	1.15	0.98	0.63	0.72	0.64
60	0.3E+06	9.51	3.08	1.51	0.87	0.55	0.33	0.25	0.17	0.12	0.09
70	0.3E+06	9.50	3.37	1.86	1.22	0.99	0.69	0.55	0.46	0.39	0.34
80	0.3E+06	9.24	3.53	2.05	1.42	1.04	0.85	0.70	0.59	0.52	0.46
90	0.3E+06	4.63	1.55	0.79	0.48	0.31	0.22	0.16	0.12	0.09	0.07
100	0.3E+06	1.11	0.27	0.10	0.05	0.02	0.01	0.01	0.00	0.00	0.00
110	0.3E+06	0.13	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
120	0.3E+06	0.00	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.0	0.0
130	0.3E+06	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
140	0.3E+06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
150	0.3E+06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
160	0.3E+06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
170	0.3E+06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
180	0.3E+06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
190	0.3E+06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
200	0.3E+06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
210	0.3E+06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
220	0.3E+06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
230	0.3E+06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
240	0.3E+06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
250	0.3E+06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
260	0.3E+06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
270	0.3E+06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
280	0.3E+06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
290	0.3E+06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
300	0.3E+06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
310	0.3E+06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
320	0.3E+06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
330	0.3E+06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
340	0.3E+06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
350	0.3E+06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
360	0.3E+06	0.00	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

APPENDIX E

PARASITISM

The concept of parasitic disease forecasts was introduced in Chapter 1, section 1.6.2.

E.1 Climatic indices and development rates

In general, the interpretation of climate as a measure of disease incidence has followed two distinct lines of enquiry. The first makes use of climatic factors known to influence the development of the parasite during its stages of free existence on pasture (Figure E.1). When these factors are examined over a period of years they can lead to a *climatic index* which co-ordinates with disease incidence. Ollerenshaw and Smith (1969) have achieved estimates of both disease intensity and timing in this way.

The second line of enquiry uses biological development rates, calculated from the behaviour of parasites studied in constant temperature chambers under laboratory conditions to deduce the influence of temperature variation on the development of parasites in the field. These development rates, when combined with reproduction and mortality rates of the parasite during its various development stages, enable a mathematical model to be constructed and the prediction of the size and development of the parasite population on a given day.

Laboratory and "small plot" studies cannot necessarily be related to fluctuating microclimatic conditions in the field (Levine, 1963 and 1980; Crofton, 1964; Thomas and Starr, 1978). However, such studies have made it possible to establish threshold development temperatures and development and mortality rates (Andersen *et al*., 1966; Pandey, 1972). These data have in turn led to mathematical models of population dynamics which, when matched with field data, do seem to confirm that conventional meteorological observations can be correlated with epidemiological findings (Tallis and Donald, 1970; Levine and Andersen, 1973; Hirsch, 1977; Callinan, 1977; Young *et al*., 1980; Grenfell and Smith, 1983).

Some examples and case-studies are now presented of both approaches to parasitic disease incidence forecasting.

E.1.1 Nematodiriasis - climatic indices

Ollerenshaw and Smith (1969) have successfully used average soil temperatures for March in central England as a guide to nematodiriasis incidence. The index is a measure of the degree of coincidence of grazing with the onset of pasture contamination by the Nematodirus worms (Figure E.2(a). Thus, in the United Kingdom, late springs, as designated by low March soil temperatures, pose potential problems. The Ministry of Agriculture, Fisheries and Food (MAFF) issues routine forecasts for the disease (Figure E.2(b)).

A graphical presentation by Ollerenshaw (1980) of cumulative seasonal percentage departures of temperatures and rainfall from the mean allows estimates of the likely incidence of nematodiriasis to be monitored throughout the winter. Figure E.3 illustrates how the likely nematodiriasis disease rating was assessed following the winter of 1978/1979 (see also Appendix C, section C.3.1.4). Although providing a useful guide, intelligent monitoring is necessary and the disease levels in 1954 did not acccord with weather analysis due to a very dry April which delayed herbage infection until May.

E.1.2 Liver fluke disease (fascioliasis) - climatic indices

Studies of historical disease and weather records confirm the importance of pasture "wetness" and a 10°C threshold temperature for the proliferation of the snail host *L. truncatula* and for the mobility of the infective larvae (cercariae) (Figure E.4).

Using climatic and veterinary information from North Wales, United Kingdom, Ollerenshaw and Rowlands (1959) were able to estimate the likely severity of the summer and winter disease incidence in the United Kingdom by deriving a climatic index (M_t). M_t is a function of monthly rainfall, potential transpiration and rain days and is weighted for a threshold development temperature of 10°C (Figure E.5(a) and (b)). No allowance can be made for animal stocking density or snail population. Nevertheless, the accumulation of M_t allows a timely estimate of the likely disease incidence the following spring due to the overwintering infection and the summer infection, and the M_t index has, for many years, formed the basis for operational forecasts issued by the MAFF of England and Wales which suggests whether anthelmintic control measures might be relaxed or intensified. Similar systems have been tried in Ireland (Ross, 1978) and France (Leimbacher, 1978; Gruner and Boulard, 1982) (Figure E.5(c)).

If farmers heed the warnings, disease levels will be low and offer no check on whether the forecast would have been correct! There is evidence that the forecasts do form a basis for management decisions among some United Kingdom farmers.

E.1.2.1 Fascioliasis - development fractions

Recently Gettinby *et al*. (1979), Gettinby and Paton (1981), Paton and Thomas (1983), Grenfell and Smith (1983) and Gardiner (1983) have reported on models that predict parasite populations both on pasture and in the host. Such mathematical models of epidemiology and population dynamics allow an assessment of the relative impacts of various control strategies. These management aids fall into two groups - analytical and simulation models. Wilson *et al*. (1982) examined parasitic population dynamics using both these approaches. The former are useful in the determination of strategic disease control policies (Hirsch, 1977) (Figure E.6); they are essentially simple models. Simulation models, on the other hand, are designed to reveal the optimum tactical control procedures under local circumstances. Here every possible biological and physical factor must be included; external factors affecting performance can be systematically changed, the components being checked by appeal to field findings (Figures E.7 and E.8).

The basis of a simulation modelling approach by Gettinby and Gardiner (1980) is to assume that parasitic development responds predictably to temperatures such that in a constant temperature enclosure (above the threshold for development), development will be completed after a fixed time (we may choose to define this time as when 50 per cent of the parasites have developed/emerged). Development times obtained at various temperatures must be manipulated if they are to be usefully extrapolated to fluctuating field temperatures.

If a stage requires D(T) days to develop at constant temperature T, then daily fractional development is $\frac{1}{D(\underline{T})}$. For a stage experiencing different constant temperatures $\bar{T}_1$, $\bar{T}_2$, T_3 ..... on days 1, 2, 3, ..., development will be completed on day n when $\Sigma \frac{T}{D(T_n)} \geq 1$ (Gettinby and Gardiner, 1980).

In field situations, diurnal variation can be taken into account by using $\frac{T_x + T_n}{2}$,

where: T_x = maximum temperature;
T_n = minimum temperature.

The daily development fraction must be weighted by the fraction "a" according to the proportion of the day during which development proceeds. Thus:

$a = 1$ when $T_n \geq T_r$, the threshold development temperature,

but $a = \frac{T_x - T_r}{T_x - T_n}$ when $T_n < T_r$

and T now becomes $\frac{T_x + T_r}{2}$

Thus, under fluctuating temperatures, development occurs when

$$\Sigma \frac{a_n}{D(T_n)} \geq 1$$

The development times formed the basis for an earlier forecasting model by Gettinby (1974) which predicted not only the population of metacercariae on the grazed pasture but the larval burden within the stock. To achieve this the faecal pellet distribution, egg population and probability of the miracidae encountering a snail host were modelled.

E.1.2.1.1 Fascioliasis control

Controls attempt to break the life cycle by treating the animal or snail or by segregating the hosts. The first is achieved by flukicides (reducing the egg output), the second by pasture treatment with molluscicides (removing snails and hence adult fluke populations) and the third by fencing off snail habitats or by drainage. The costs of these control policies must be balanced against the benefit of decreased damage to stock. Cost-benefit analyses could optimize timing and type of control.

Using simulation techniques Gettinby (1974), Hope Cawdrey <u>et al</u>. (1978) and Gettinby and McClean (1979) proposed how to assess the success of the timing of certain of these control techniques and to assess the lower

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limits of pastural contamination and snail survival rates below which control is uneconomical. However, deficiencies in biological data (e.g. the degree of damage as a function of fluke infection) probably militate against the application of cost-benefit analysis techniques for the present.

E.1.3 Parasitic gastro-enteritis (pge) - ostertagiasis - climate indices

Several parasite species are responsible for pge in sheep, cattle, etc. Unlike the fluke, development does not require passage through the snail or other secondary hosts. Again, summer and winter infections can occur in temperate zones (Thomas, 1982).

Regression indices were identified by Ollerenshaw and Smith (1969) for the early and late summer ostertagiasis in sheep and cattle. Rainfall or soil moisture deficit and the observed disease rating in a previous season figure in the equation. There are considerable differences in the grazing rates of sheep and cattle and in the different micro-environments for larvae in the faecal pats of cattle compared with the smaller, easily broken pellets of sheep. These are just some aspects that greatly influence the dynamics of the parasite life cycle (Gettinby and Gardiner, 1980).

Thomas and Starr (1978) and Starr and Thomas (1980) describe useful models for timing the onset of the summer larval burden in the United Kingdom using the concept of larval development proceeding at a rate depending on "thermal time" when pastures are moist. Mortality rates and field intelligence of egg concentrations could be incorporated to make the procedure semi-quantitative. Such models have been used in the United Kingdom for broad guidance on the onset of high pasture larval burdens.

E.1.3.1 Development fractions and ostertagiasis

Gettinby and Paton (1981) and Grenfell and Smith (1983) describe prediction models for bovine ostertagiasis and Paton and Thomas (1983) for ostertagiasis in lambs based on development fraction techniques. Contamination levels were predicted by Paton and Thomas (1983) both for the absence of controls and for the application of drug treatments.

Indications were that, for example, for weather conditions favourable for parasite transmission, dosing of lambs in early June could substantially reduce the magnitude of the summer wave of infection to which lambs are exposed. On the other hand, the impact of late June treatments on the summer wave will be small. Thus the model predicts that even initially clean pastures can make a very significant contribution to the summer wave of infection.

The model of Grenfell and Smith is illustrated in Figure E.9. It comprises nine coupled first-order differential equations which describe the rate at which parasites enter and leave various stages in the life cycle. The model again successfully mimics the typical field disease pattern in the presence and absence of anthelmintic controls.

All the results of model studies suggest that standard meteorological records of temperature and rainfall used with suitably specified parameters of parasitic performance can predict levels of infective larvae on pasture and indicate the efficiency and timeliness of control measures.

E.1.4 Management alternatives for control

The recognition that helmintic diseases are weather-sensitive offers control alternatives. The farmer may have the capital to carry out drainage improvements, but he may be too heavily stocked to have adequate worm-free grazing, and molluscicide application is often impractical.

A farmer may decide to carry out a routine control programme, accepting that this level is necessary only in high incidence years; in doing so, control costs must be recovered through increased stocking rates. The farmer must sacrifice some flexibility in his husbandry operations or add to production costs. The extent to which he is prepared to adjust his farming practices will depend largely on the frequency and magnitude of disease occurrence, the extent it interferes, for example, with herbage use and the resulting profitability of the enterprise.

The alternative approach recognizes that disease levels vary, with weather playing a dominant role, and that not all farming attains a uniformly high standard. Control then aims at limiting parasite population, the degree of control varying from year to year. This approach recognizes that there are other desirable objectives such as the eradication of disease and the control of sub-clinical parasitism. It also suggests that there must be a priority in disease control, namely, to undertake control by the most efficient means at the most advantageous times, appropriate to the expected disease intensity but allowing flexibility with regard to stock and pasture management. Limitations in husbandry practices are then only made when there is a real need - efficient control at the lowest cost (Ollerenshaw and Smith, 1969; Gettinby, 1974).

E.1.5 Ectoparasites

Haufe (1978) discussed how meteorological services can be of subsequent advantage in defining the seasonability of ectoparasites such as the horn-fly, haematobia irritants. Local synoptic meteorological data are used to advantage in Canada in forecasting the relative abundance of successive fly generations for economic scheduling of control programmes.

Gordon *et al*. (1981) described how these weather inputs may be used in beef-forage-grain simulation models to select the optimum economic control practice for ectoparasites in various kinds of farm operations in different agricultural environments.

E.1.5.1 Ticks

Encouraging progress is reported with the modelling of the seasonal pattern of tick populations (Donnelly, 1978; Gardiner, 1983). The complex tick cycle makes this a difficult challenge, but one worth accepting since *I. ricinus* is the known vector of a great variety of pathogens such as tick-borne encephalitis in Turkey and other parts of Europe and the USSR and red water fever and louping ill elsewhere.

The epidemiologies of other ectoparasitic diseases are described in Gibson (1978). Modelling approaches to the population dynamics of east coast fever and mosquito-borne diseases would be invaluable to their prediction and control.

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There are no demonstrable examples of practical applications of meteorological inputs in hot climates due to lack of direct assessments of the influence of meteorological factors in host-ectoparasite relations.

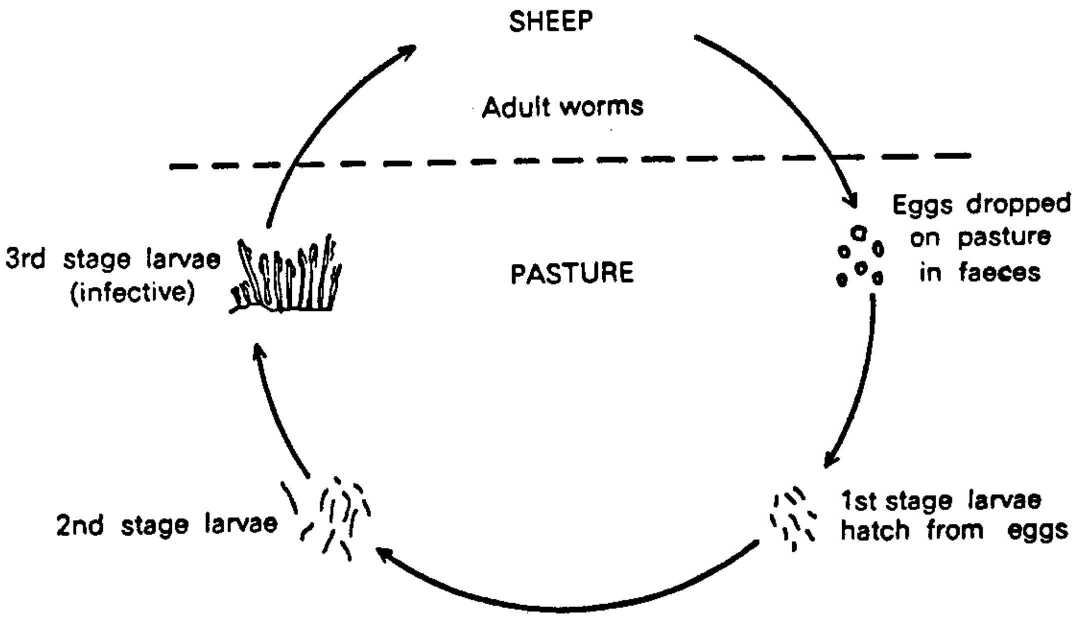


Figure E.1 - Typical roundworm (nematode) life history

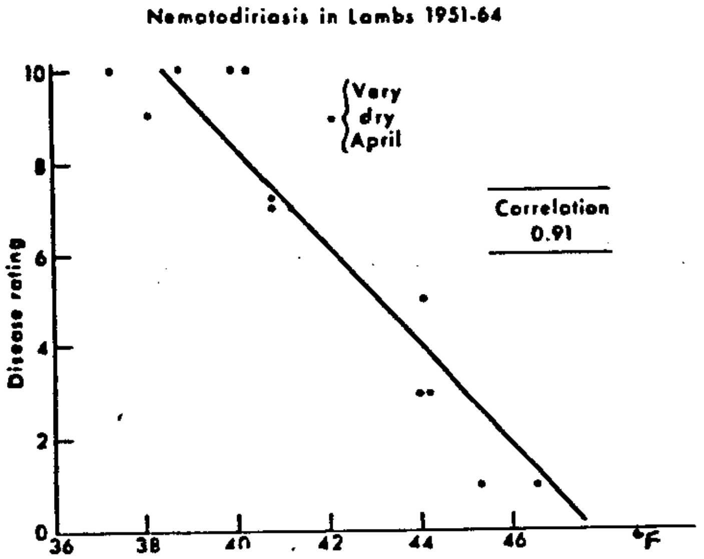
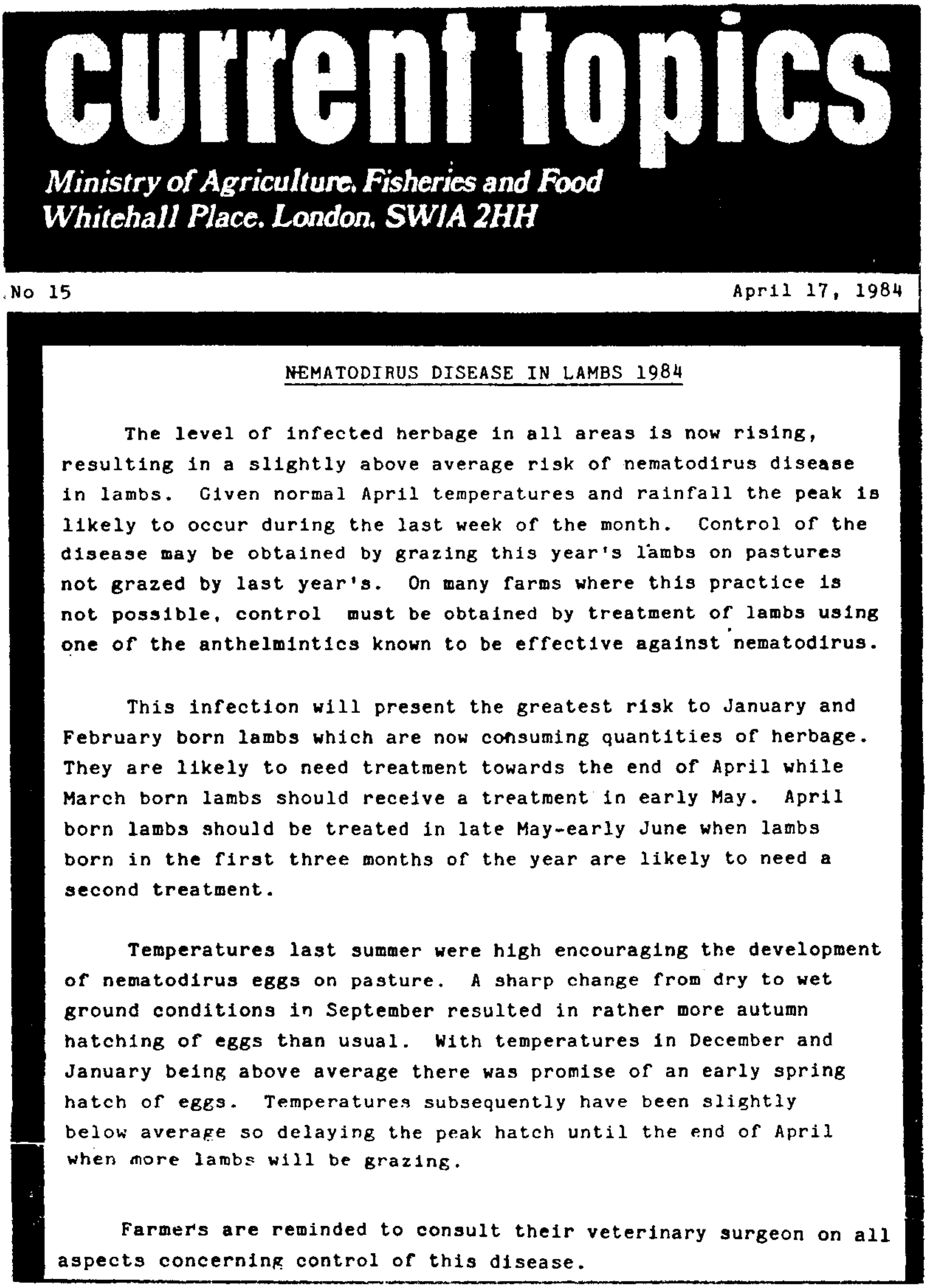


Figure E.2(a) - Relationship between severity of nematodiriasis in lambs and 30 cm March soil temperatures (Oxford)



current topics

Ministry of Agriculture, Fisheries and Food
Whitehall Place, London, SW1A 2HH

No 15

April 17, 1984

NEMATODIRUS DISEASE IN LAMBS 1984

The level of infected herbage in all areas is now rising, resulting in a slightly above average risk of nematodirus disease in lambs. Given normal April temperatures and rainfall the peak is likely to occur during the last week of the month. Control of the disease may be obtained by grazing this year's lambs on pastures not grazed by last year's. On many farms where this practice is not possible, control must be obtained by treatment of lambs using one of the anthelmintics known to be effective against nematodirus.

This infection will present the greatest risk to January and February born lambs which are now consuming quantities of herbage. They are likely to need treatment towards the end of April while March born lambs should receive a treatment in early May. April born lambs should be treated in late May-early June when lambs born in the first three months of the year are likely to need a second treatment.

Temperatures last summer were high encouraging the development of nematodirus eggs on pasture. A sharp change from dry to wet ground conditions in September resulted in rather more autumn hatching of eggs than usual. With temperatures in December and January being above average there was promise of an early spring hatch of eggs. Temperatures subsequently have been slightly below average so delaying the peak hatch until the end of April when more lambs will be grazing.

Farmers are reminded to consult their veterinary surgeon on all aspects concerning control of this disease.

Figure E.2(b) - A sample bulletin

Temperature and rainfall in 1978 and 1979 over England and Wales relative to the long-term average

Month	November	December	January	February	March	Total
Temperature °C	+1·7	−0·3	−3·0	−2·2	−1·0	−4·8
Rainfall %	45	230	100	104	191	670

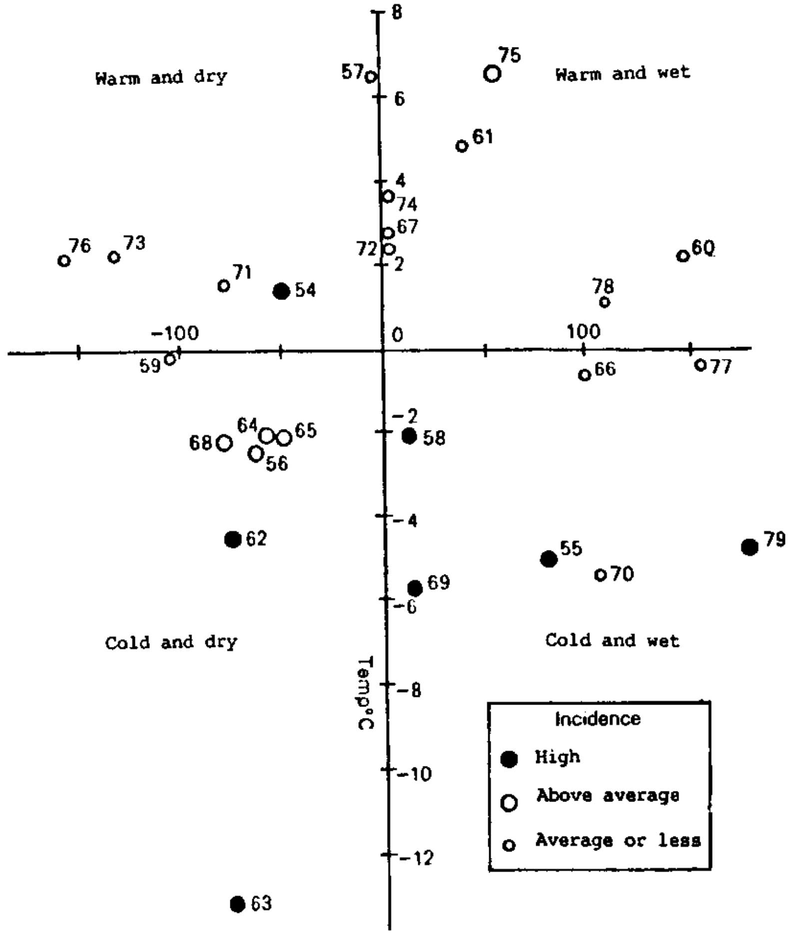


Figure E.3 - Nematodiriasis disease assessment based on temperature and rainfall (Ollerenshaw, 1980)

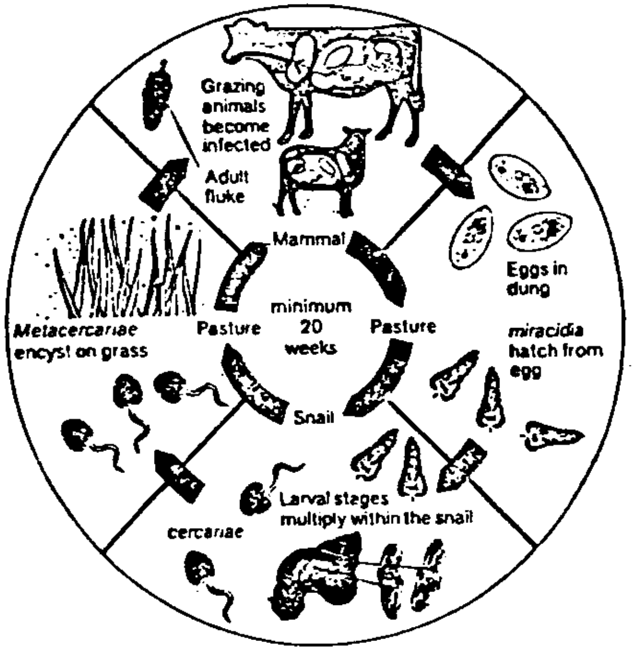


Figure E.4 - Life cycle of the liver fluke (Spectrum (ICI) 1 (7), September 1981)

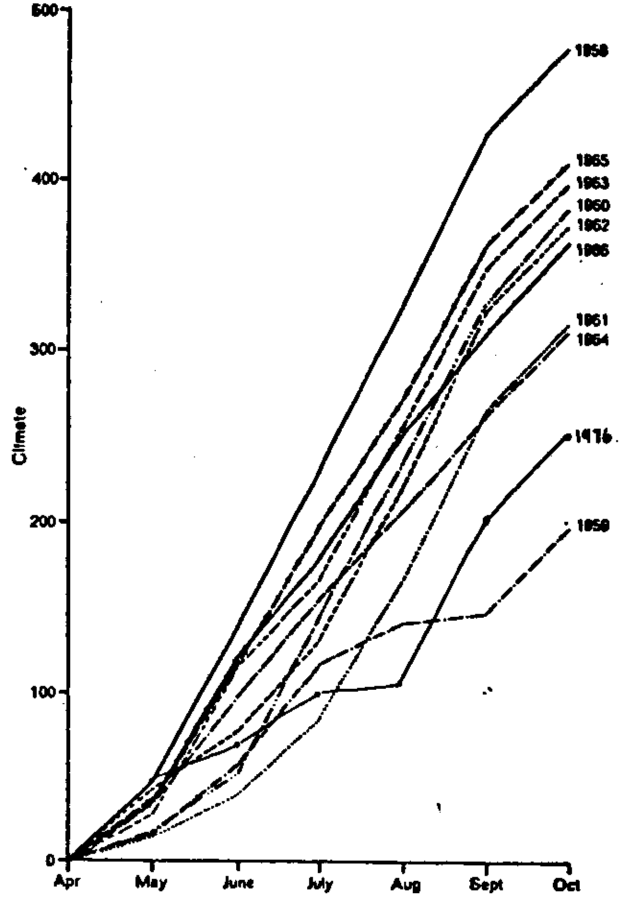


Figure E.5(a) - Cumulative values of climate (M_t) from May to October 1958-1966, using the average values from 11 meteorological stations in Wales (United Kingdom) (Ollerenshaw, 1967)

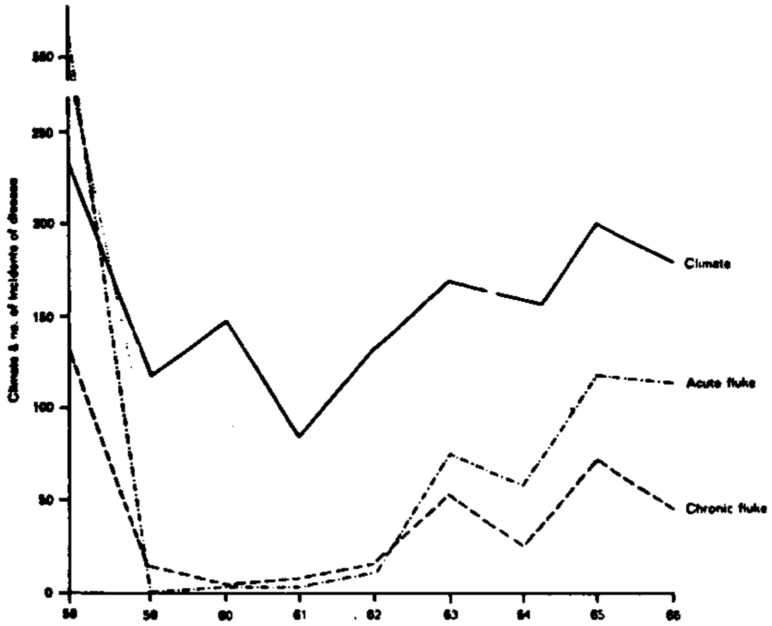
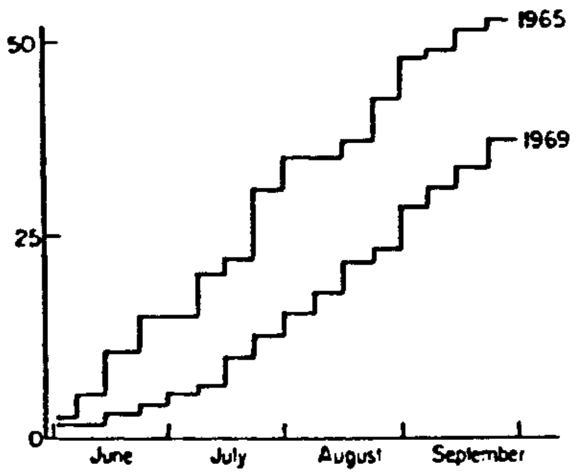
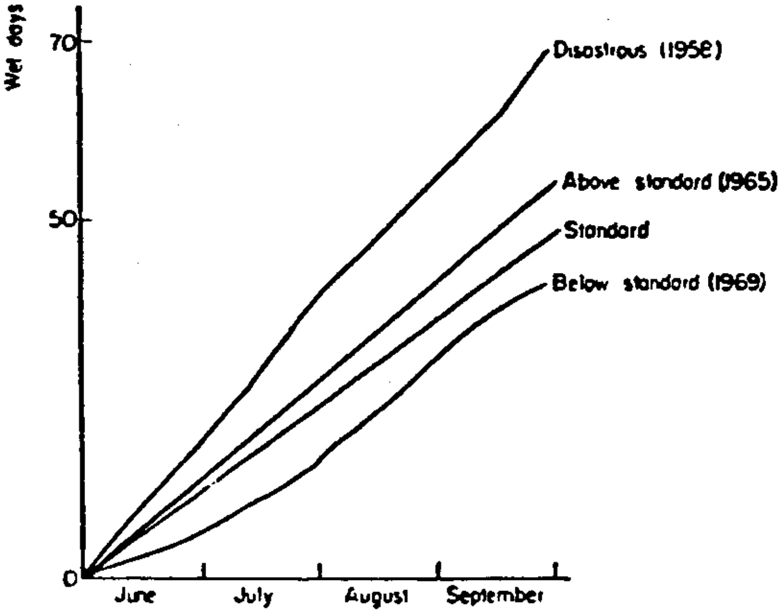


Figure E.5(b) - A comparison between climate (M_t value to the end of July) and the incidence of acute fluke and chronic fluke diseases in sheep diagnosed by the three veterinary investigation centres in Wales, (United Kingdom), 1958-1966 (Ollerenshaw, 1967)

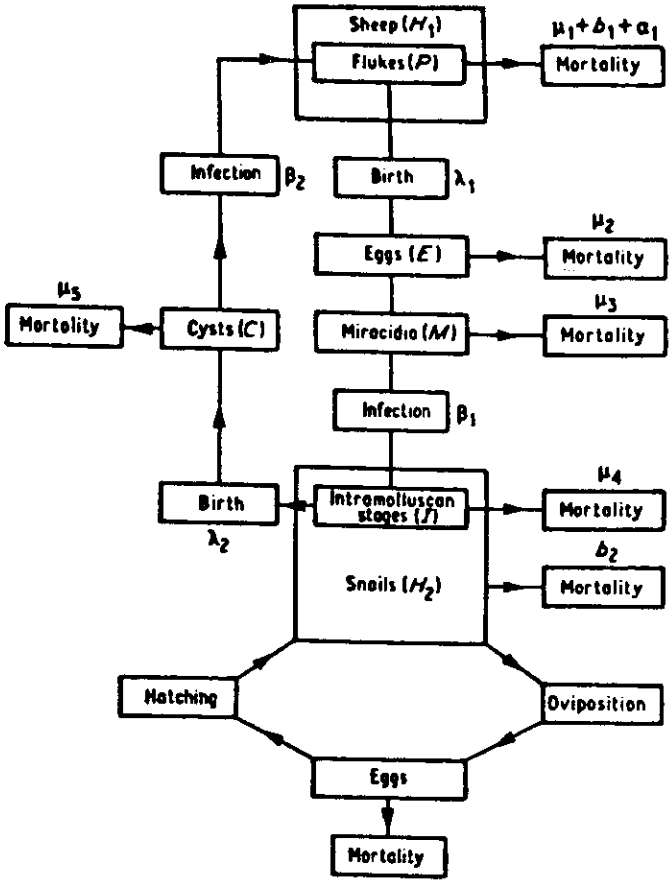


(i)



(ii)

Figure E.5(c) - (i) Accumulative "wet-day" graph for one eastern area in an above-standard year, 1965, and a below-standard year, 1969; (ii) comparative accumulative "wet-day" graph for four grades of liver fluke infection years in Ireland (Gibson, 1978)

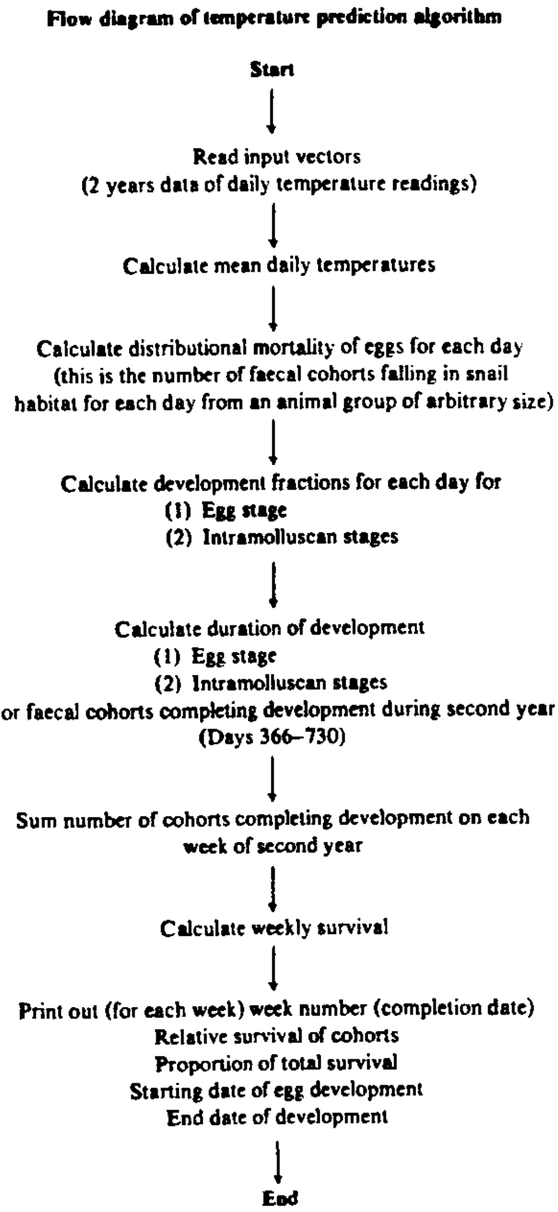


Explanation of symbols

P (t) : Flukes at time t
E (t) : Fluke eggs at time t
M (t) : Miracidia at time t
C (t) : Cysts on the herbage at time t
H_1 : Sheep density
H_2 : Snail density
a : Parasite-induced host mortality
b : Natural host mortality
β : Instantaneous infection rates
λ : Specific rates of fecundity
μ : Specific rates of mortality

Figure E.6 - A mathematical model flow chart giving the life cycle of *Fasciola hepatica* (fluke and *Lymnaea truncatula* (snail)) (Anderson, 1982)

APPENDIX E



Flow diagram of temperature prediction algorithm

Start

↓

Read input vectors
(2 years data of daily temperature readings)

↓

Calculate mean daily temperatures

↓

Calculate distributional mortality of eggs for each day
(this is the number of faecal cohorts falling in snail
habitat for each day from an animal group of arbitrary size)

↓

Calculate development fractions for each day for
(1) Egg stage
(2) Intramolluscan stages

↓

Calculate duration of development
(1) Egg stage
(2) Intramolluscan stages
For faecal cohorts completing development during second year
(Days 366–730)

↓

Sum number of cohorts completing development on each
week of second year

↓

Calculate weekly survival

↓

Print out (for each week) week number (completion date)
Relative survival of cohorts
Proportion of total survival
Starting date of egg development
End date of development

↓

End

Figure E.7 – The flow diagram of the basic temperature algorithm for predicting prevalence of liver fluke disease. Various modifications such as limiting effects of moisture stress can be superimposed on this algorithm (Gibson, 1978)

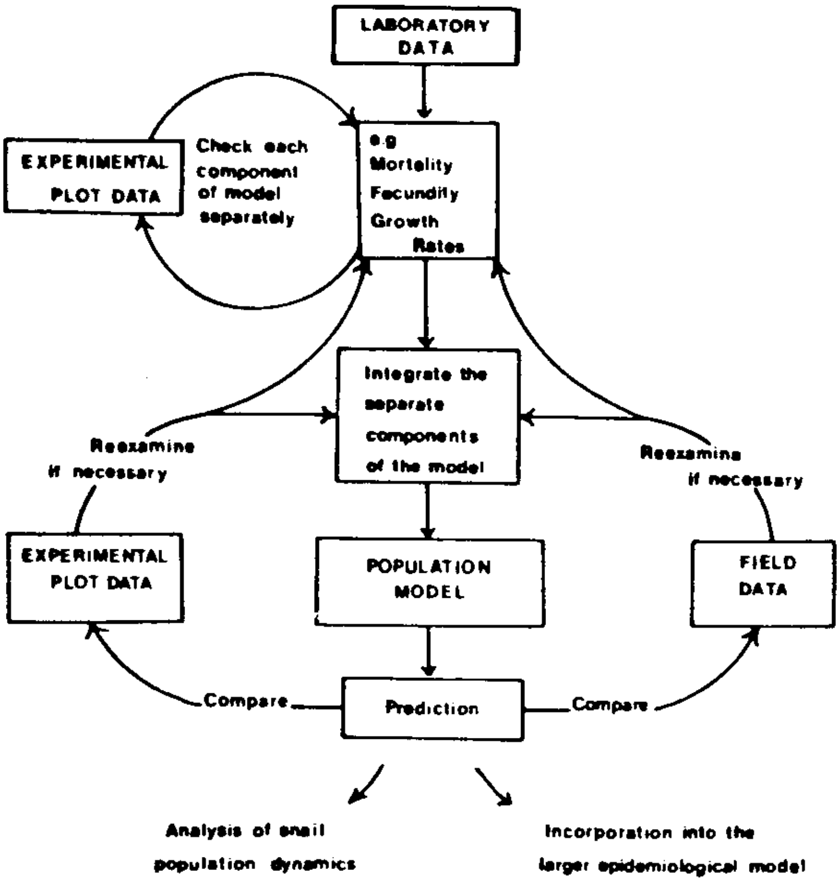


Figure E.8 - A diagram of part of the process of building a complex model (Gibson, 1978)

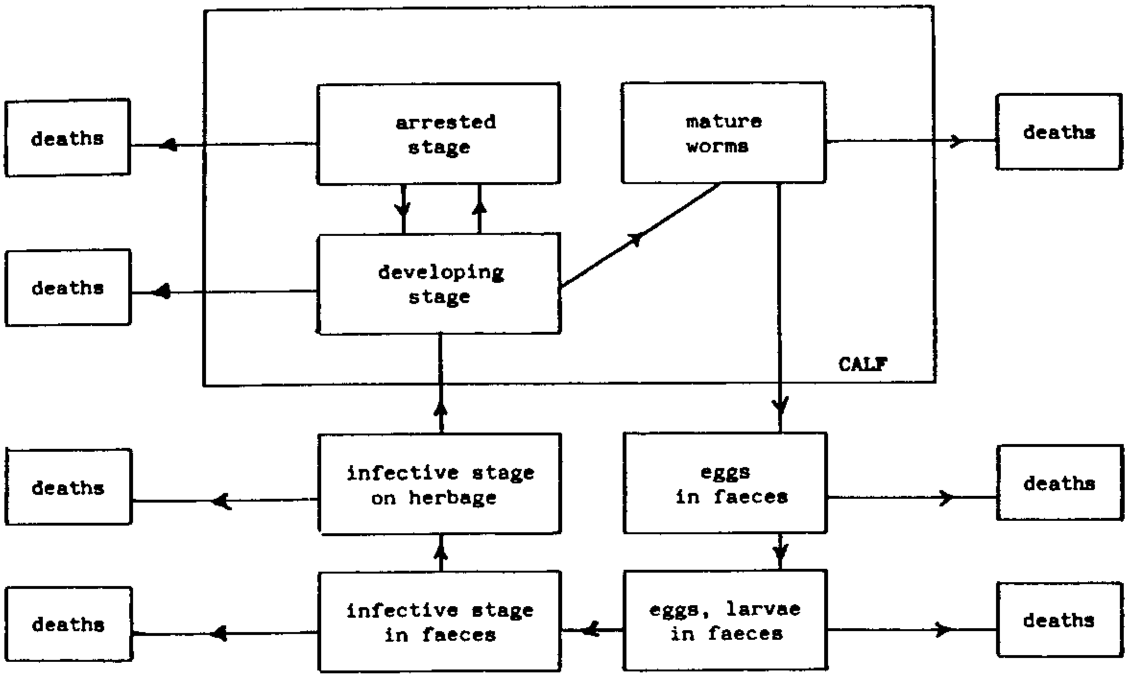


Figure E.9 - Life cycle of O. ostertagi (Grenfell and Smith, 1983)

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