SIMULATION OF HAY-MAKING SYSTEMS
by
M.L. GUPTA

ERRATA

Page 23 Item (iv): "investigation of hay-making..." to read "inclusion of hay-making policy models in order to investigate hay-making with respect to start date, swath area limit and weather prospects after cutting, as described in Section 1.5."

Page 52 3rd paragraph: "... studies by Dalton." to read "... studies by Dalton (Rose, 1966)."

Page 57 3rd paragraph: "... kleingrass, coastal Bermuda grass and perennial sweet sorgrass." to read "... kleingrass (Panicum Coloratum L.), coastal Bermuda grass (Cyndon dactylon (L.) Pers.) and perennial sweet sorgrass (Bothriochloa Pertusa L (?))".

Page 58 1st and 2nd paragraphs: replace "crop" with "grass".

Page 67 Last paragraph: "... fescue, orchardgrass, bromegrass, alfalfa-timothy, and alfalfa-fescue..." to read "... fescue (Festuca arundinacea Schreb.), orchardgrass (Dactylis glomerata L.), bromegrass (Bromus inermis Leyss.), alfalfa-timothy (Medicago Sativa L.-Phelum pratense L.) and alfalfa-fescue (Medicago Sativa L.-Festuca arundinacea Schreb.)."

Page 69 2nd paragraph: "The authors" to read "Dyer and Brown".

Page 90 Last paragraph: add the following statement before the sentence "The model suggests...": "These conclusions are based on the limited data and would benefit from further investigation."

Page 104 2nd paragraph: add the following sentence at the end of this paragraph: "It may be noted that the value of R^2 is quite low and further experiments are needed to improve the prediction capacity of the above equation."

Page 158 Figure 10.3: add the following note in the caption: "(Simulations for variable and constant yield were made at the same digestibility. A slight difference is shown in the graph to illustrate the range of DDM for both the cases.)"

Page 167 2nd paragraph: replace this paragraph with the following: "Clearly, conditioning of hay results in an increase in DDM of hay and savings of labour cost following a reduction in the harvest period. However, there will be extra costs associated with the use of a conditioner, namely fixed and variable costs of using the conditioner and the cost of baling, carting and storing the additional quantity of hay. Hence, the use of a conditioner is justifiable only if the additional benefits exceed the additional costs."
Page 171  2nd paragraph: add the following sentence at the end:
"The above cost analysis does not take into account the cost of baling,
carting and storing the additional hay, and the savings of labour cost due to
reduction in harvest period."

Page 179  2nd paragraph, 2nd line:  "... was increased" to read "... was increased
above 61%"

Pages 190, 191  Item (iii): delete the following sentence: "However, the use of
a ...... 16 bales of hay."

Page 192  Delete Item (vii).

Page 196  Item (i): add the following sentence at the end:
"This would also enable the objective comparison of the early and late cut
hay policies; the amount of DDM lost by early cutting might be offset by
additional DDM available in the paddock after regrowth."

Additional Reference
SIMULATION OF HAY-MAKING SYSTEMS

by

Madan Lal Gupta

Thesis submitted for the degree of
Doctor of Philosophy

Department of Civil and Agricultural Engineering
University of Melbourne

October 1986
TO MY PARENTS
"MAKE HAY WHILE THE SUN SHINES"
ACKNOWLEDGEMENTS

I would like to express my deep gratitude to my supervisors, Mr. R.H. Macmillan, Prof. T.A. McMahon and Dr. D.W. Bennett, for their help, guidance and for the time they have given throughout this work.

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and staff of the Melbourne office. Thanks are also due to the Head, Department of Farm Power and Machinery, Punjab Agricultural University, Ludhiana, India, for granting me study leave.

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Finally, I should not forget my affectionate wife and cheerful children who have shared with me the joys and pains of the present endeavour.
ABSTRACT

In southern Australia, fodder is conserved mainly as hay, and pasture is the common raw material. This hay-making process is complex and, unlike other harvesting operations which are virtually instantaneous, involves a series of sequential operations with three or more different machines. It also involves a number of major and minor management decisions in a highly variable weather regime and with continuously changing crop conditions.

A simulation model has been developed to evaluate alternative hay-making systems and management policies in terms of the digestible dry matter (DDM) yield of hay and of the harvesting time. The main simulation is based on a series of sub-models associated with pasture growth, weather forecasts, management, hay-drying and hay losses. Some of these models are based on the available literature and others have been developed by the author. Field-drying experiments with unconditioned and conditioned pasture were conducted to develop the hay drying model which also includes the effect of dew and rain. A method was developed to make an assessment of three-day weather forecasts for scheduling hay-making operations.

Simulation experiments were carried out by using 16 years of historical weather data from Laverton, Victoria. Management factors such as weather prospects after cutting, maximum cut crop allowed in the swath and maturity at the start of season were found to affect the DDM yield and harvesting time. To achieve a
significant increase in DDM yield of hay, either an improvement in the accuracy of weather forecasting is necessary or the drying time in the field must be reduced by applying a treatment such as conditioning of the crop at the time of cutting.

The major limitation of the present simulation model is the lack of data. Research is needed to refine the loss parameters due to environmental factors and mechanical operations on which the DDM yield is based. A number of other promising research areas also are outlined to extend the use of the present model and make improvements to it.
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CHAPTER 1

INTRODUCTION

1.1 General

Fodder conservation is an important farm practice in Australian agriculture. There are two main methods of fodder conservation - hay-making and silage-making. However, most fodder is conserved as hay, and pasture is the common raw material (Figure 1.1). The average annual production of conserved fodder during the period 1975-84 was 4.43 million tonnes air dry hay equivalent, out of which 97% was hay and 3% silage (ABS, 1975-81; ABS, 1982-84). The total hay production comprised of 64% pasture, 20% cereal and 16% lucerne hay.

Thus, average annual hay production in Australia is about 4.3 million tonnes and, based on $100 t^{-1}$, has a value of $430$ million. Losses of 10-40% are common during the hay-making process (Simmons, 1981) and, based on an average loss of 25%, this involves a cost of about $108$ million. If the losses could be reduced by just 5 percentage points, about $22$ million could be saved each year.

More than half of the annual growth of pastures occurs in the spring (September – November) and their growth is small during the winter or summer (Figure 1.2). Because of this seasonal imbalance, due largely to limitations of temperature and rainfall
Figure 1.1 Fodder production in Australia.

Figure 1.2 Annual pattern of pasture growth and stock requirements (from Hosking, 1974).
respectively, farmers usually close some paddocks during the spring when the supply of pasture is surplus to the grazing animals' needs. These paddocks are then used for making hay that year. Some of the conserved hay is subsequently fed to the animals (mainly cattle) during the autumn and winter months of most years when the seasonal growth of pasture is inadequate. The balance is kept perhaps for many years and used in an occasional drought. Good farm management requires conserved fodder and stock numbers generally to be in continuous balance so that in all but the most extreme drought the farmer will have sufficient fodder reserves.

1.2 Hay-making Process

The common method of hay-making involves five steps, in sequence, as shown in Figure 1.3. After cutting (mowing) the crop, it is left out in the field for natural drying. Towards the end of drying, the crop is gathered (raked) into windrows and then at a suitable moisture content is compressed into bales or stacks. Baled hay is either left out in the field for outdoor storage or carted to the shed for indoor storage.

1.3 Hay-making Systems

A large number of different types of machines are available to perform various hay-making operations and hence there are a multitude of different systems for hay-making on farms. Figure 1.4 shows the range of hay-making systems which are presently in use in Australia.
Figure 1.3 Flow chart showing hay-making process.
Figure 1.4 Range of hay-making systems in Australia.
Three distinct phases of the hay-making process may be identified as pre-packaging, packaging, and post-packaging, which can be carried out by various machines.

The standing crop is converted into a form ready for packaging in a variety of ways. The most common method is to cut or mow the crop by traditional sickle bar or rotary disc mower, and to leave it in the swath for drying. One or more swaths are then raked into windrows in preparation for packaging. To reduce the hay drying time, sometimes the crop is conditioned immediately after mowing. Hay conditioners are of two types - crushers and crimpers. The crushers squeeze the plants longitudinally to split the stem, while the crimpers bend and crack the stems at intervals so that they split at a number of points. Thus, conditioning of crop opens new pathways of water loss by physical rupture of plant tissues. Mower-conditioners and windrowers are the alternative machines which can be used in the pre-packaging phase of hay-making.

Fodder in the form of hay usually is conserved in compressed packages of different shapes and sizes. The conventional rectangular baler is probably still the most common packaging machine on Australian farms, but is partly being superseded by big balers capable of producing round packages of up to 1000 kg. Large square balers and hay stack wagons are the two other types of packaging machines.

Post-packaging essentially involves the carting (loading, transportation, and unloading and stacking) of packaged hay to
the storage site. The small rectangular bales normally are stored in a shed and can be handled in a number of ways, which vary from completely manual handling to use of a fully automatic bale wagon. Round bales usually are left out in the field, as they are somewhat resistant to weather damage. However, these also may be stored in a shed if they are to be kept for a longer period, in which case various machines can be employed for transport of one or more bales to the storage site.

1.4 The Objective Function

The true value of hay can be assessed only in terms of animal production. Hay which is able to produce greater amounts of milk, meat or wool is obviously better. However, there are a number of other criteria such as digestible dry matter, available energy, digestible organic matter and total digestible nutrients, which can be used to represent the value of hay (Pigden, 1969). For this study, digestible dry matter (DDM) was chosen as a criterion for comparing the performance of hay-making systems. The DDM is a function of both the quantity and quality of crop. Quantity is represented in terms of dry matter (DM) yield (t ha⁻¹), whereas digestibility can be taken as a measure of quality. Hay quality improves with earlier cutting; however, yield normally increases as the cutting is delayed (Figure 1.5). It is therefore more useful to express yield of conserved hay in terms of DDM (= DM x digestibility) as an inverse relationship exists between increasing DM yield and decreasing digestibility.
Figure 1.5 Changes in DM yield, digestibility and DDM yield during the haymaking season (from Cayley, 1974).
1.5 Need for the Study

The main cause of losses during hay-making may be identified as
(i) respiration losses as the crop continues to be alive after cutting,
(ii) mechanical losses due to handling of crop at various stages of the hay-making process, and
(iii) leaching and other losses due to rain.

These loss processes are not independent of each other and depend to a marked degree on the weather. The problem with hay-making is therefore to so manage the process that the hay is cut, dried and baled in the best available weather. Unlike many other harvesting operations which are virtually instantaneous, hay-making involves a series of sequential operations which when commenced (for any given area) by the cutting must be completed irrespective of the prevailing weather.

Hay-making is an exceedingly complex process but present management methods are limited to experience, intuition and guess work. Presumably these provide a less-than-optimum management strategy. However, it is considered that this situation can be improved by a rational analysis of the various processes. Many of these are inadequately understood and the present work is intended to form the structure of a simulation which will provide an analysis of the overall process and identify the important variables. It is hoped that this in turn will encourage a more detailed study of the individual processes and a further improvement of the simulation.
The aim of any hay-making system is to preserve as much of the quantity and quality of standing crop as possible. Because of the variation in DDM yield of standing pasture during the season, the first question that arises is, 'what is the optimum date to start hay-making?' If it could be carried out instantaneously, obviously the optimum date would be the time when the DDM yield of standing crop is at its maximum (Figure 1.5). However, in practice the harvest takes a considerable period of time and thus there is no simple way to answer this question. The optimum date is likely to be a function of various factors such as the total crop to be harvested, the type and size of machines used for hay-making, the weather pattern during the season and policies to be followed in day-to-day management of the hay-making operations.

The weather prospects are represented by the forecasts, both the informal ones by the farmer himself and the more formal three-day forecast provided by the Bureau of Meteorology. These are of course not always correct and this introduces a significant element of uncertainty into the plans made by the farmer.

Once the decision to start the season has been made, the continuing questions for the farmer at each stage through the season are, 'should more hay be cut and, if so, how much?' The answer to both questions depends on when rain will occur and what the weather up to that time will be like. For example, if the weather will be hot and dry, more hay could be cut and it may be possible to complete the harvesting of both the newly-cut hay and that already lying in the swath. On the other hand if the weather will be cool with low drying capacity, it may not even be
possible to harvest what has already been cut before rain falls.

Superimposed on this decision-making, in the context of an imperfect weather forecast, are two other factors which are changing during the season. The first is the general improvement in the weather for hay-making, that is, fewer wet days, higher evaporation and longer dry spells (Figure 1.6). The second is the continuously changing (increasing then decreasing) potential DDM of the standing crop as shown in Figure 1.5.

A conservative policy in relation to the immediate avoidance of weather damage may mean that much of the harvest is delayed to a stage when DDM is decreasing, but the weather is more suitable for hay-making. However, the planned area may then not be finished before the end of season. On the other hand, a more aggressive policy which proposes cutting (almost) irrespective of the weather prospects will mean more high quality crop is exposed to possible weather damage and this could cause a decrease in total DDM if rain occurs.

The time between cutting of the pasture and drying to the moisture content suitable for packaging is mainly dependent on the weather and the machinery used for pre-packaging operations. Since there are various machines available to perform the pre-packaging operations and these also influence the drying rate, it is possible to reduce the time of exposure of cut crop in the field by conditioning it. This will minimise the weather risk and increase the DDM of hay due to reduction of field losses. Another way to reduce the drying time is to bale the hay at a higher than
Figure 1.6 Weather during the hay-making season (based on data from McMahon and Srikantan, 1983).
normal moisture content and treat it with preservatives for safe storage.

From the above discussion, it can be remarked that there are a number of policies (represented by start date, weather prospects after cutting and maximum cut crop allowed in the swath for cutting to proceed) which can be used to complete the hay-making process for a given area by a given machinery system. However, presumably there exists an optimum policy (or policies) to secure the maximum amount of DDM of hay whilst completing the harvest under variable and unpredictable weather. Such decisions now are being made intuitively by farmers. However, a simulation model has the potential to go further by taking into account, in a rational way, the many factors such as crop growth during the season, historical weather information, weather forecasts, and type and size of hay-making systems.

One could of course evaluate various machinery systems and management policies by carrying out field experiments for several years. However, such experiments are expensive and require a long period of time. The simulation approach, on the other hand, is a quick and relatively inexpensive method of comparing the performance of hay-making systems.

Considering all these factors, this study is undertaken to develop a simulation model of hay-making to produce information on relative performance of various hay-making systems and management policies.
1.6 Objectives

The specific objectives of this study are:

(i) To develop a simulation model of hay-making. The model should be versatile enough to allow the analysis of various hay-making systems and management techniques.

(ii) To demonstrate an application of the model in establishing an optimum hay-making policy for a given area and machinery system.

(iii) To investigate the effect of the following factors on the performance of various systems:
(a) conditioning the crop at the time of cutting,
(b) baling at a higher moisture content and treating hay with preservatives,
(c) accurate long-term weather forecasts,
(d) system capacity, and
(e) manpower.

1.7 Format of the Thesis

Chapter 2 provides a review of literature on the development of mathematical models related to hay-making together with the requirements of a simulation model for Australian conditions. An overview of the hay-making simulation model is presented in Chapter 3 wherein the scope of the model and structure of the simulation program are described. The next 6 chapters describe the development of various sub-models of the main simulation program. Growth of pasture is discussed in Chapter 4, while Chapter 5 reviews the literature related to hay drying and also
presents the swath hay drying model based on the field experiments. The development of a baled hay drying model is described in Chapter 6 and the method of estimating losses during hay-making is given in Chapter 7. Analysis of weather forecast data and its use in making weather forecasts as well as their assessment in hay-making are presented in Chapter 8. Chapter 9 describes a management model which is used to schedule the hay-making operations according to the weather forecasts and quantities of hay lying in the field. The simulation results are presented in Chapter 10. Finally, Chapter 11 gives the conclusions of this study and recommendations for future research.
CHAPTER 2

LITERATURE REVIEW

Hay-making is an extremely complex process involving, as it does, a series of major and minor management decisions in a highly variable weather regime and with continuously changing crop conditions. Systems approaches such as the use of optimisation and simulation techniques have been employed to analyse hay-making systems. In this chapter, a review is presented of those studies which have considered the complete hay-making process. In later chapters, literature relevant to the development of various sub-models is reviewed.

2.1 Optimisation Models

Because of the complexity of optimisation models in general, those applied to hay-making have involved a considerable simplification of the physical process and are restricted to the particular application.

A number of models involving optimisation techniques such as linear programming (Tseng and Mears, 1975), mixed integer programming (Taylor, 1971; Amir et al., 1978a; Amir et al., 1978b) and Lagrange multiplier and Separable programming (Cunney and Von Bargen, 1972) have been developed in the past 15 years or so to analyse hay-making systems. However, these optimisation models are unable to handle adequately the stochastic and
dynamic aspects of the hay-making process which were discussed in Section 1.5, and are considered necessary for adequate modelling of the hay-making process in southern Australia. For example, the yield and digestibility of crop, which varies with the stage of growth, and the scheduling of operations, which needs detailed analysis of the weather, have not been realistically modelled. Because of the various practical inadequacies of optimisation models, simulation models have been developed to accommodate the complex time-dependent operations in hay-making.

2.2 Simulation Models

Simulation models are inherently simpler than models involving optimisation and they provide greater facility for modelling, in a realistic manner, the complex management aspects of the hay-making process as practised in Australia. In the past, models of varying degrees of sophistication have been developed overseas to help solve hay-making system selection and management problems. Early models did not include the drying process but included simple and unsubstantiated deterministic rules. However, recent simulation studies have incorporated drying models in an attempt to more realistically simulate this aspect of the process. Hay-making simulation models are broadly classified into those which do not simulate the drying process and those which do; both these categories are reviewed in the following sections.
2.2.1 Models without simulation of the drying process

In an attempt to investigate the effect of various harvesting systems and starting dates on milk production, Cloud et al. (1968) used a very simple simulation technique. They designated a day as either rainy or clear. A rainy day was defined as a 24-hour period starting at 17.00 h in which more than a trace of rain fell. The harvest policy considered the state of the overall harvest process and allowed mowing to occur on every clear day as long as the crop cut and lying on the ground was not more than the 1-day harvest capacity of the system. However, instead of a proper drying model, the rather simplified approach used to schedule the harvesting operation was that hay could be harvested the day after cutting but, if the cut crop was rained on, two extra clear days in succession were required before harvesting could begin. Different loss values were assumed for hay not rained on, for hay which was rained on for 1-5 days and for more than 5 days.

Fuller (1969) investigated the effects of different machinery systems in a 2-cut harvest using a very simple model. Based on historical weather data, he classified days as work or non-work days according to rain and no-rain respectively, and used these to simulate the hay-making operations. A major simplification was that the time required to dry hay under rain or no-rain conditions was kept fixed and was an input to the model. Further, the losses due to weather were taken into account but they were kept constant irrespective of the amount of rain.
Miller and Rehkugler (1972) developed a simulation model to determine the optimum harvest start date for various harvesting rates (6, 12, 18 and 24 t day⁻¹) to maximise milk production. Two types of hay-making systems were considered; a 1-day system requiring one dry day and a 2-day system requiring two consecutive dry days. They found that the optimum start date was different for different harvest rates and that the start date could be delayed for large harvest rates to achieve maximum milk production. This simulation was more realistic than many others in that it took into account the effect of yield and quality of standing alfalfa as a function of the number of calendar days of growth. However, the losses during hay-making were not considered. The day-by-day simulation was carried out simply by comparing the probability of "bad" weather (based on historical weather data) on a given day with a random number between 0.00 and 1.00 generated by a computer subroutine. If the random number was higher than the probability value, then the weather was assumed to be suitable for harvesting and vice versa. Since, the overall harvest rate was specified, no detailed simulation of the individual operations such as cutting, drying, raking, baling and carting was carried out.

Cunney and Von Bargen (1974) developed a simulation model to compare two systems of forage harvesting. This simulation essentially mimicked the daily operations of two machines (windrower and baler or stack former) which worked sequentially on the same area advancing to new areas as weather allowed. They found that average dry matter yields were very similar for both systems but the stacking system resulted in a reduction of time
by about 25%. The large capacity systems resulted in a small
decrease in yield due to a shorter growth period. The simulation
technique used by them was quite different and an improvement
from the previous studies discussed above, particularly in
relation to the harvesting time increment. They divided a day
into three periods: 10.00 to 16.00 h and 16.00 to 22.00 h, the
two half-day work periods; and 22.00 to 10.00 h, the non-working
period. Based on the amount of rainfall during the previous two
days and on the current day, the work periods were classified
into three types which were used to schedule different hay-making
operations. The method of estimating losses during hay-making was
superior to other studies as the losses were determined as a
function of amount of rainfall and number of days that the crop
remained in the field. However, no detailed simulation of the
drying process was carried out and, instead, it was assumed that
hay could be baled in the fourth work period or it could be
stacked in the third work period after cutting, irrespective of
weather conditions.

The above studies which simulated the hay-making process had a
number of major deficiencies. The management policy was simulated
with simple work/no work rules. A fixed drying period was used
for rain or no-rain conditions but apart from rain, the drying
time is dependent upon other meteorological factors such as
temperature, relative humidity, wind speed and radiation which
were not included. Losses during hay-making either were not taken
into account or fixed losses were used irrespective of actual
weather conditions. Dale et al. (1978) highlighted the importance
of including a drying model in the hay-making simulation as well
as the estimation of losses due to the respiration process, mowing, raking and baling operations.

2.2.2 Models with simulation of the drying process

Bebernes and Danas (1978), in developing their simulation model for alfalfa harvesting, computed natural drying time using a drying model which incorporated features such as overnight dew and rainfall between cutting and baling. They included losses due to rainfall while determining the total losses of a given harvesting system. Little detail of the simulation procedure is given in their paper but it appears that the model provides for cutting the whole crop area at one time, unlike the common practice of making hay in small lots as the season progresses.

The simulation model developed by Parke et al. (1978) at the National Institute of Agricultural Engineering (NIAE), Silsoe, UK, was, perhaps, the first attempt to adequately simulate the drying process and to estimate the losses as a function of weather conditions encountered during hay-making. However, the drying model used was based on the work by Spatz et al. (1970) in which the crop was tedded a number of times; this is not a common practice in Australia. The model also did not take into account the effect of dew at night. Further, the crop growth model was not a function of weather during hay-making - instead, it was simply a function of the number of calendar days of growth.

The application of the above model to investigate the effect of increased drying rates and use of preservatives for hay baled at
a higher moisture content also was demonstrated by Dumont et al. (1979) and Boyce et al. (1980). The effect of these two factors on system performance are also investigated in this project.

More recent publications related to hay-making simulation are due to Lovering and McIsaac (1981), McIsaac and Lovering (1982), Pitt (1982), Russell et al. (1983) and Savoie et al. (1985); all make use of drying models and estimate losses as well. However, all these models are based on the multi-cut harvest of a crop and their drying models are not for a ryegrass/ryegrass-clover, which is a major crop for making hay in Australia. Also, their drying models predict changes in moisture content on a daily basis only. In order to analyse hay-making systems more realistically, the model should be able to estimate the moisture content at any given time during the day so that a more detailed scheduling of hay-making operations such as cutting, raking, baling or carting can be carried out. Another limitation of these models is that they use a fixed hay-making policy during the simulation; there is little provision to consider a number of policies to determine the optimum one. These studies also have not considered the weather forecasts which are important during hay-making.

2.3 A Model for Australian Conditions

One of the peculiar characteristics of all the models (excluding the one developed by Parke and others) described in Section 2.2 is that they are for crops which are cut more than once during a year. Since pasture is a common raw material for making hay in Australia, which is normally cut once in a year, we need a model
which is suitable for a single-cut system and also a drying model
must be suitable for this crop. The model developed at NIAE could
have been useful for Australian conditions as it was based on a
single-cut forage conservation system. However, it had a number
of inadequacies in relation to Australian conditions and the
present work as discussed earlier.

Hence, the present thesis is aimed at developing a hay-making
simulation model for Australian conditions by incorporating
features not included in the above models. These are:
(i) use of a pasture growth model which could predict the yield
and quality of standing crop as a function of weather;
(ii) development of a hay drying model for rye-grass/clover
pasture which could predict the moisture content at any
time during the day;
(iii) consideration of weather forecasts and their adequate
analysis; and
(iv) investigation of hay-making policies with respect to start
date, swath area limit and weather prospects after cutting
as described in Section 1.5.
CHAPTER 3

OVERVIEW OF HAY-MAKING SIMULATION MODEL

Simulation is a technique that involves setting up a model of a real situation (system), and then performing experiments on the model (Naylor et al., 1966). Thus, simulation is essentially a two-phase process involving modelling and experimentation. The modelling phase of simulation involves development of a mathematical model of a system suitable for operation on a computer. The experimentation phase of simulation is similar in many respects to physical experimentation with the system.

This chapter gives a brief description of the hay-making simulation model along with its scope. Detailed descriptions of various parts of the model are given in the next six chapters. The simulation experiments are described in Chapter 10.

3.1 Scope of Simulation

The main objective of this thesis is to develop a simulation model of hay-making which will allow the evaluation of various hay-making systems and management policies. As discussed in Section 1.5, the simulation seeks to clarify the essentially practical issues which must be considered in the management of any hay-making system.
The major components of the hay-making simulation model are shown in Figure 3.1. Pasture is taken as an input material for making hay and its harvest is considered only once a year. Once the paddock is closed for fodder conservation, the growth of pasture is assumed to be affected by the weather (temperature, rainfall and evaporation) alone. Several other factors such as grazing management and weather prior to the closing of the paddock, soil type, pasture species, pests and disease also are likely to influence the growth of pasture but these are not included in the present simulation. The effect of making hay on pasture regrowth in the following years also is not taken into account when comparing the performance of hay-making systems.

An important requirement of the hay-making simulation is to keep records of the quantity and condition of hay between the time it is cut and the time it is put into store. Thus, the growth of pasture is simulated on a daily basis and the hay-making activities (machinery operations, field-drying of hay and quantitative and qualitative changes in hay) are simulated on an hourly basis. The machinery operations are influenced by the plans made by the management and actual weather at the time of operations. These plans depend upon the amount, moisture content and state of cut crop lying in the field, weather forecasts, and the availability of labour and machinery for hay-making (Figure 3.1).

The simulation is stopped when all the hay is in store, and no attempt is made to simulate the storage and subsequent feeding of hay to animals. Consequently, the value of hay is not converted
Figure 3.1 Major components of hay-making simulation model.
to animal product such as milk, meat or wool, and instead, digestible dry matter (DDM) yield of conserved hay in the store is taken as a performance parameter for comparing various systems and management policies.

3.2 Simulation Structure

A model, named HAYSIM (for HAYmaking SImulation Model), was developed in the FORTRAN 77 language. A listing of the computer program HAYSIM and a sample output are given in Appendix A. The main simulation is based on a series of sub-models associated with pasture growth, weather forecasts, management, hay drying and hay losses. Detailed descriptions of these models are given in Chapters 4 to 9. In this section HAYSIM is briefly discussed with the help of a flow chart of the program (Figure 3.2).

3.2.1 System data

The model starts by reading input data related to the system, which includes information such as total area planned for hay-making, performance rates of machinery, manpower and management policy.

Management policy describes mainly the decision criteria for the cutting operation which are:

(i) maximum digestibility at the start of season,

(ii) minimum digestibility below which no further cutting is worthwhile,

(iii) minimum revised probability of three dry days, and
Figure 3.2 Simplified flow diagram of the hay-making simulation model.
(iv) swath area limit.

The digestibility criteria are used to represent crop maturity at the start and end of season. If the digestibility of growing pasture is higher than the maximum value, the start of season is postponed on the assumption that the pasture is still too immature. On the other hand, if the digestibility falls below the minimum value, no more cutting is allowed on the assumption that the pasture quality is too low to be worth making hay.

The minimum revised probability of three dry days is used to represent the risk a farmer is prepared to take in regard to weather prospects between the time hay is cut to the time it is ready for baling. Higher required probability values will delay the cutting whereas lower values will put more hay at a higher risk of adverse weather.

Swath area limit is expressed as a number of days of harvest capacity of the system. This is used to represent the risk a farmer is prepared to take with respect to having large or small quantities of hay lying in the swath. A large swath limit will allow hay-making to occur at a faster rate than a lower swath limit, but more hay will be at the risk of adverse weather at any given time.

3.2.2 Start of season

Before the actual simulation process for each season starts, historical weather data are read for one season. Currently, up to
100 days' data can be read for each season. The following data items define the weather conditions on each day:

(i) daily rainfall, mm (09.00-09.00 h)
(ii) rain during the night, mm (20.00-06.00 h)
(iii) mean vapour pressure deficit during the night, kPa (20.00-06.00 h)
(iv) mean temperature during the night, °C (20.00-06.00 h)
(v) hourly vapour pressure deficit, kPa (06.00-20.00 h)
(vi) hourly global radiation, MJ m⁻² (06.00-20.00 h)
(vii) hourly wind speed, m s⁻¹ (06.00-20.00 h)
(viii) hourly rainfall, mm (06.00-20.00 h)
(ix) hourly temperature, °C (06.00-20.00 h)

Depending upon the availability of weather information, three different levels of hourly weather data can be used to run the model:

Level 1 - data items include (v), (viii) and (ix)
Level 2 - data items include (v), (vi), (viii) and (ix)
Level 3 - data items include (v), (vi), (vii), (viii) and (ix).

At the start of each season, the hay-making status is also initialized to keep an account of area yet to cut, area in store and number of hay plots in different states. A plot is defined here as an area which is cut, raked, baled or carted in an hour.

3.2.3 Start of day

When the pasture has reached a suitable stage of maturity and is ready for harvesting, the hay-making process is started. The
areas cut, raked, baled and carted, and times spent for each of these operations are intialized at the start of each day. For the purpose of this simulation, a day has been defined from 09.00 to 09.00 h on the next day, and is divided into following periods:

(i) working period - from 09.00 to 20.00 h, with 13.00 to 14.00 h being a meal break, and

(ii) non-working period - from 20.00 to 09.00 h.

3.2.4 Simulation methodology

A daily routine is started at 09.00 h when a weather forecast for three days is made using historical weather data and forecast accuracy. The three-day weather forecast is used to revise the probability of experiencing three dry days. This is done to simulate the farmer's judgement of the weather which he makes based on his perception of weather pattern through his experience and the confidence he has in the forecast. Then the dry matter yield, digestibility and moisture content of standing crop are predicted using a pasture growth model. Using the revised probability of three dry days and the status of hay-making, such as the amount and state of cut crop lying in swath and baled hay lying in the field, the management model prepares the operations schedule for a specified interval of time ranging from one to several hours.

Once the plan is made, an hourly routine is started which performs the hay-making operations according to the schedule and updates the attributes (moisture content, dry matter yield and digestibility) of hay lying in the field. A swath hay
model was especially developed for ryegrass-clover pasture to update the moisture content of hay lying in the swath. The moisture content of hay bales, not yet carted to the store, is determined using a baled hay drying model. Based on published information in the literature, quantitative and qualitative losses due to mechanical operations and environmental factors are estimated to update the yield and digestibility of hay.

After the specified interval of time (given in the input), the hay-making status is again updated and a new plan of operations is made. The hourly routine ends at 20.00 h when the routine for the non-working period is started. During this period no hay-making operations are carried out but the attributes of hay lying in the field are updated. In this way the simulation continues for a number of days until all the area is harvested or the last day of the season is reached.

The simulation is then repeated for the next year. Each year's weather data is replicated a number of times (specified in the input) using different random numbers which determine the weather forecast sequence. At present, the model can be run for up to a maximum of 25 years with 10 replications for each year. The limit is as a result of array dimensions which can be easily altered. After the simulation is repeated for a given number of years, the mean, minimum, maximum and standard deviation of parameters such as total DDM of the conserved hay and harvesting time are computed.
3.2.5 Linking the sub-models

The structure of the HAYSIM program is designed in such a manner that its computational procedure is broken down into a number of specific tasks, each of which is carried out by an individual subroutine or group of subroutines. This simplifies maintenance and updating of the model because existing subroutines can be replaced readily by improved versions, and new subroutines can be added to include additional capabilities.

The simulation model consists of a main program and twenty-one subroutines. Figure 3.3 is a diagrammatic representation of the linkages between the programs. In this figure, a link between two program 'boxes' indicates that the program on the right is a subroutine which is called at least once by the program on the left. Consequently, any subroutine which is called by more than one program appears more than once on this figure. The main program itself is named HAYSIM and is responsible for reading system data, initializing the status at the start of each season and each day of the season and calling subroutines in sequence during a simulation run. A brief description of each of the subroutines shown in Figure 3.3 is given in Table 3.1.
Figure 3.3 HAYSIM program linkages.
<table>
<thead>
<tr>
<th>Subroutine</th>
<th>Frequency</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>WEATHER</td>
<td>Yearly</td>
<td>Reads weather data for each season.</td>
</tr>
<tr>
<td>PASTURE</td>
<td>Daily</td>
<td>Predicts yield, digestibility and moisture content of growing pasture.</td>
</tr>
<tr>
<td>FORECAST</td>
<td>Daily</td>
<td>Prepares 3-day forecast and estimates the revised probability of experiencing different types of 3-day weather.</td>
</tr>
<tr>
<td>MANAGEMENT</td>
<td>Variable</td>
<td>Prepares a schedule of operations at a decision time based on the feasibility and priority of operations.</td>
</tr>
<tr>
<td></td>
<td>(hourly)</td>
<td></td>
</tr>
<tr>
<td>TRANSFER</td>
<td>Depends upon rainfall</td>
<td>Changes the state of wet raked hay into unraked hay.</td>
</tr>
<tr>
<td>OPERATIONS</td>
<td>Hourly</td>
<td>Performs operations according to the schedule.</td>
</tr>
<tr>
<td>CUTTING</td>
<td>Depends upon schedule</td>
<td>Transfers one hour's worth of crop from 'uncut' to 'cut' state.</td>
</tr>
<tr>
<td>RAKING</td>
<td>Depends upon schedule</td>
<td>Transfers one hour's worth of crop from 'unraked' to 'raked' state.</td>
</tr>
<tr>
<td>BALING</td>
<td>Depends upon schedule</td>
<td>Transfers one hour's worth of crop from 'raked' to 'baled' state.</td>
</tr>
<tr>
<td>CARTING</td>
<td>Depends upon schedule</td>
<td>Transfers one hour's worth of baled hay from field to store.</td>
</tr>
<tr>
<td>STATUSHOUR</td>
<td>Hourly</td>
<td>Updates the status (MC, yield and digestibility of each plot) of hay-making during each hour of the day from 06.00 to 20.00 h.</td>
</tr>
<tr>
<td>Subroutine</td>
<td>Frequency</td>
<td>Purpose</td>
</tr>
<tr>
<td>------------</td>
<td>-------------------------------</td>
<td>-------------------------------------------------------------------------</td>
</tr>
<tr>
<td>RAINYHOUR</td>
<td>Each rainy hour</td>
<td>Determines increase in moisture content due to rainfall during each rainy hour between 06.00 to 20.00 h.</td>
</tr>
<tr>
<td>DRYHOUR</td>
<td>Each rain-free hour</td>
<td>Determines drying rate of hay during each rain-free hour between 06.00 to 20.00 h.</td>
</tr>
<tr>
<td>LEACHING</td>
<td>Rainy hour or rainy night</td>
<td>Determines leaching losses due to rainfall.</td>
</tr>
<tr>
<td>RESPIRATION</td>
<td>Hourly from 06.00 to 20.00 h and once during night</td>
<td>Determines dry matter losses due to respiration.</td>
</tr>
<tr>
<td>STATUSNIGHT</td>
<td>Once during night</td>
<td>Updates the status of hay-making during each night.</td>
</tr>
<tr>
<td>RAINYNIGHT</td>
<td>During a rainy night</td>
<td>Determines increase in moisture content during a rainy night.</td>
</tr>
<tr>
<td>DRYNIGHT</td>
<td>During a rain-free night</td>
<td>Determines change in moisture content during a rain-free night.</td>
</tr>
<tr>
<td>ENDYR</td>
<td>Yearly</td>
<td>Stores the results for each season. Also prints the results for each day of the season, if required.</td>
</tr>
<tr>
<td>RESULT</td>
<td>Once</td>
<td>Writes the summary results for each season at the end of simulation.</td>
</tr>
<tr>
<td>SUMMARY</td>
<td>Yearly</td>
<td>Determines mean, minimum, maximum and standard deviation of each output variable.</td>
</tr>
</tbody>
</table>
Although pasture grows throughout the year, the main growth occurs during the spring months. Farmers usually close some paddocks early in that period and later in that year use them for making hay. The yield and quality of pasture are dependent on the closing date and closing period (Ryan, 1966; McGowan, 1978; Cayley, 1974). As the pasture hay crop matures it changes from a leafy to a stemmy state, a process which results in a decrease in digestibility and thus in the quality of the hay it produces. However, yield normally increases as the crop becomes mature, reaches a peak and then starts falling as leaves die and shatter, and seedheads drop (Simmons, 1964). This chapter describes a growth model which predicts these changes in the yield and digestibility of conserved pasture after its closure, and provides a basis for comparing the performance of hay-making systems.

4.1 Program PASTURE

White et al. (1983) developed a pasture growth model for northern Victoria which predicts the yield and digestibility of annual pasture when it is being grazed around the year. This model has been modified to predict changes in the yield and digestibility of perennial pastures in western Victoria (Bowman, 1985).
For this project, the GROWTH subroutine of Bowman's model was modified to predict the yield and digestibility of standing pasture kept for hay-making. A computer program PASTURE was written in FORTRAN 77 for this purpose, the listing of which is given in Appendix B. The program logic is shown in Figures 4.1 and 4.2. A detailed review of how this model operates is beyond the scope of the present work but this is the only model available and widely used in southern Australia.

The input data requirements for the program are:

(i) Daily rainfall
(ii) Daily class A pan evaporation
(iii) Weekly average temperature
(iv) Potential growth rate of pasture
(v) Field capacity and wilting point of upper soil zone
   (0 - 200 mm) and lower soil zone (200 - 1000 mm)
(vi) Week of the year when the paddock was closed (NP)
(vii) Starting values for soil moisture and pasture availability

4.1.1 Weather data

Weather data for Laverton, Victoria, were procured from the Bureau of Meteorology, Melbourne. Since the hay-making simulation model uses hourly data (Section 3.2.2), Laverton was chosen from the limited number of meteorological stations which keep hourly records of temperatures, radiation and rainfall. Daily rainfall and temperatures data were available since 1941 but the evaporation data were available only from 1976 onwards. In order to estimate the pan evaporation prior to 1976, a regression
Figure 4.1 Flow chart of main program PASTURE.
START

REDUCE POTENTIAL GROWTH RATE IF MEAN AIR TEMP. IS LESS THAN $10^\circ$C

DETERMINE ACTUAL EVAPOTRANSPIRATION

UPDATE UPPER AND LOWER SOIL MOISTURE ZONES

ADVANCE FLOWERING TIME IF PASTURE DRIES OFF

ESTIMATE TRANSFER OF GREEN PASTURE TO DEAD PASTURE POOL

DETERMINE DIGESTIBILITY OF GREEN AND DEAD PASTURE

DETERMINE DECOMPOSITION OF PASTURE

PREDICT ACTUAL PASTURE GROWTH RATE

UPDATE AVAILABILITY OF GREEN AND DEAD PASTURE

RETURN

Figure 4.2 Flow chart of subroutine GROWTH.
equation was developed which uses average vapour pressure deficit and daily global radiation. The wind speed data were not used because these were not available prior to 1976. The equation has the form:

\[ \text{EVAP} = 4.494 \text{ VPD} + 0.119 \text{ RAD} \]  \hspace{1cm} (4.1)

where \( \text{EVAP} \) = daily class A pan evaporation, mm  
\( \text{VPD} \) = average vapour pressure deficit during the day, kPa  
\( \text{RAD} \) = daily global radiation, MJ m\(^{-2}\)

Average vapour pressure deficits were determined using three hourly dry and wet bulb temperatures. Eight years (1976-1983) of data for the months of September to December (952 cases) were used to develop the equation. The multiple regression analysis subprogram available in SPSS\(^K\) package (Noursis, 1983) was used to analyse the data. The multiple coefficient of determination (\( R^2 \)) value is 0.70 and the standard error of estimate (SE) is 1.57.

The regression was forced through the origin because of the physical grounds which suggest that if the independent variables, VPD and RAD, are zero there should be no evaporation. In the statistical packages the way \( R^2 \) is calculated for the regression through the origin is misleading, causing an over-estimation of the adequacy of the fit (Gordon, 1981). This is because the total sum of squares is computed through the origin rather than about the mean. Thus, the \( R^2 \) value was calculated using the corrected sum of squares through the mean.
4.1.2 Pasture data

The potential growth rate of a pasture for a particular time of year is defined here as the rate which applies when soil moisture is not limiting and the quantity of green herbage in the pasture is optimal for growth. These rates were not available for this region of Victoria and hence estimates were made based on the data from Pastoral Research Institute, Hamilton, Victoria (Figure 4.3). These data were obtained under experimental conditions where the soils are more fertile. In the model, therefore, the data were reduced by 20% to bring them closer to local farm levels. The pasture was assumed to be closed at the end of the 35th week of the year. The starting value of pasture availability was set at 1000 kg ha⁻¹, green and dead pasture being 900 and 100 kg ha⁻¹ respectively. These values were based on the results of Bowman's pasture growth model (Bowman, 1985).

4.1.3 Soil data

The soils in the region to which the weather data apply are mainly red-brown earths for which the following data were obtained from the literature (Stace et al., 1968). The field capacity and wilting point of the upper soil zone were determined as 81 mm and 48 mm respectively, whereas for the lower zone these values were 432 mm and 256 mm respectively. The soil moisture was assumed to be 50% of available water between wilting point and field capacity. Accordingly, the starting values of soil moisture were set at 65 mm and 345 mm for the upper and lower zones respectively.
Figure 4.3 Potential growth rate of perennial pasture at Hamilton in Western Victoria.
4.2 Pasture Growth Equations

Daily predictions of yield and digestibility were essential for
the purpose of this hay-making simulation but the PASTURE program
only predicts these at weekly intervals. In order to interpolate
to a daily basis, the weather data for 16 years (1968-1983) were
used to run the program to estimate changes in yield and
digestibility for weeks 36-52 during each year. This 16-year
period includes both favourable and unfavourable hay-making
seasons. The output was transformed into the form shown in
Appendix C so that yield and digestibility could be determined
depending upon the day of season. In this appendix "Day" refers
to the number of days after 30 September.

A multiple regression analysis subprogram available in the SPSS^X
package (Noursis, 1983) was used to relate yield and
digestibility to day of year for each of the 16 years. Equations
of the following form were developed:

\[ y = a_0 + a_1 x + a_2 x^2 \]  \hspace{1cm} (4.2)

A step-wise regression was used to delete the non-significant
variables at the 0.05 level of significance for all the
equations.

The parameters for the regression equations for dry matter yield
and digestibility are given in Table 4.1 and Table 4.2
respectively together with the values of R^2 and SE. To illustrate
these equations graphically, the growth curves for the two
Table 4.1 Regression analysis for dry matter yield of pasture.

<table>
<thead>
<tr>
<th>Year</th>
<th>Constant ($a_0$)</th>
<th>Regression coefficient for Day ($a_1$)</th>
<th>Regression coefficient for Day² ($a_2$)</th>
<th>$R^2$</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1968</td>
<td>2.187</td>
<td>0.0311</td>
<td>-0.000308</td>
<td>0.97</td>
<td>0.068</td>
</tr>
<tr>
<td>1969</td>
<td>2.272</td>
<td>0.0509</td>
<td>-0.000443</td>
<td>0.93</td>
<td>0.127</td>
</tr>
<tr>
<td>1970</td>
<td>2.443</td>
<td>0.0421</td>
<td>-0.000401</td>
<td>0.94</td>
<td>0.087</td>
</tr>
<tr>
<td>1971</td>
<td>2.434</td>
<td>0.0936</td>
<td>-0.000790</td>
<td>0.96</td>
<td>0.188</td>
</tr>
<tr>
<td>1972</td>
<td>2.055</td>
<td>0.0312</td>
<td>-0.000237</td>
<td>0.94</td>
<td>0.081</td>
</tr>
<tr>
<td>1973</td>
<td>2.231</td>
<td>0.0629</td>
<td>-0.000561</td>
<td>0.99</td>
<td>0.069</td>
</tr>
<tr>
<td>1974</td>
<td>2.455</td>
<td>0.1199</td>
<td>-0.001024</td>
<td>0.93</td>
<td>0.305</td>
</tr>
<tr>
<td>1975</td>
<td>2.279</td>
<td>0.1322</td>
<td>-0.001086</td>
<td>0.96</td>
<td>0.266</td>
</tr>
<tr>
<td>1976</td>
<td>2.305</td>
<td>0.1285</td>
<td>-0.001086</td>
<td>0.95</td>
<td>0.283</td>
</tr>
<tr>
<td>1977</td>
<td>2.629</td>
<td>0.0396</td>
<td>-0.000321</td>
<td>0.78</td>
<td>0.213</td>
</tr>
<tr>
<td>1978</td>
<td>2.430</td>
<td>0.0693</td>
<td>-0.000559</td>
<td>0.98</td>
<td>0.098</td>
</tr>
<tr>
<td>1979</td>
<td>2.347</td>
<td>0.1187</td>
<td>-0.000972</td>
<td>0.94</td>
<td>0.310</td>
</tr>
<tr>
<td>1980</td>
<td>1.503</td>
<td>0.0673</td>
<td>-0.000492</td>
<td>0.99</td>
<td>0.091</td>
</tr>
<tr>
<td>1981</td>
<td>1.950</td>
<td>0.0412</td>
<td>-0.000288</td>
<td>0.99</td>
<td>0.053</td>
</tr>
<tr>
<td>1982</td>
<td>2.333</td>
<td>0.0373</td>
<td>-0.000346</td>
<td>0.90</td>
<td>0.109</td>
</tr>
<tr>
<td>1983</td>
<td>2.260</td>
<td>0.1261</td>
<td>-0.001016</td>
<td>0.95</td>
<td>0.293</td>
</tr>
</tbody>
</table>

Table 4.2 Regression analysis for digestibility of pasture.

<table>
<thead>
<tr>
<th>Year</th>
<th>Constant ($a_0$)</th>
<th>Regression coefficient for Day ($a_1$)</th>
<th>Regression coefficient for Day² ($a_2$)</th>
<th>$R^2$</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1968</td>
<td>0.761</td>
<td>-0.0068</td>
<td>0.0000428</td>
<td>0.99</td>
<td>0.010</td>
</tr>
<tr>
<td>1969</td>
<td>0.779</td>
<td>-0.0060</td>
<td>0.0000300</td>
<td>0.97</td>
<td>0.019</td>
</tr>
<tr>
<td>1970</td>
<td>0.763</td>
<td>-0.0055</td>
<td>0.0000235</td>
<td>0.99</td>
<td>0.012</td>
</tr>
<tr>
<td>1971</td>
<td>0.755</td>
<td>-0.0019</td>
<td>-0.0000149</td>
<td>0.98</td>
<td>0.016</td>
</tr>
<tr>
<td>1972</td>
<td>0.757</td>
<td>-0.0064</td>
<td>0.0000385</td>
<td>0.98</td>
<td>0.012</td>
</tr>
<tr>
<td>1973</td>
<td>0.767</td>
<td>-0.0048</td>
<td>0.0000156</td>
<td>0.96</td>
<td>0.021</td>
</tr>
<tr>
<td>1974</td>
<td>0.782</td>
<td>-0.0034</td>
<td></td>
<td>0.92</td>
<td>0.030</td>
</tr>
<tr>
<td>1975</td>
<td>0.784</td>
<td>-0.0032</td>
<td></td>
<td>0.94</td>
<td>0.025</td>
</tr>
<tr>
<td>1976</td>
<td>0.786</td>
<td>-0.0034</td>
<td></td>
<td>0.94</td>
<td>0.028</td>
</tr>
<tr>
<td>1977</td>
<td>0.785</td>
<td>-0.0070</td>
<td>0.0000410</td>
<td>0.97</td>
<td>0.020</td>
</tr>
<tr>
<td>1978</td>
<td>0.756</td>
<td>-0.0026</td>
<td>-0.0000081</td>
<td>0.99</td>
<td>0.009</td>
</tr>
<tr>
<td>1979</td>
<td>0.784</td>
<td>-0.0034</td>
<td></td>
<td>0.93</td>
<td>0.029</td>
</tr>
<tr>
<td>1980</td>
<td>0.684</td>
<td>-0.0024</td>
<td></td>
<td>0.93</td>
<td>0.020</td>
</tr>
<tr>
<td>1981</td>
<td>0.737</td>
<td>-0.0054</td>
<td>0.0000293</td>
<td>0.99</td>
<td>0.008</td>
</tr>
<tr>
<td>1982</td>
<td>0.777</td>
<td>-0.0068</td>
<td>0.0000395</td>
<td>0.97</td>
<td>0.018</td>
</tr>
<tr>
<td>1983</td>
<td>0.783</td>
<td>-0.0032</td>
<td></td>
<td>0.94</td>
<td>0.025</td>
</tr>
</tbody>
</table>
extreme years (1968 and 1983) are shown as an example in Figure 4.4. Note the large variations in yield and digestibility due to seasonal weather conditions.

4.3 Moisture Content of Growing Pasture

The moisture content of growing pasture varies with the growth stage. As the plants become mature, the moisture content decreases (Mitchell and Shepperson, 1955; Hart and Burton, 1967; Parrott and Donald, 1970; Green et al., 1971). However, no experimental data were available which could help relate the moisture content of pasture with weather conditions. Based on the limited information available from the literature (Parrott and Donald, 1970; Barber and Pratt, 1980; Barber, 1985) and field-drying experiments (Chapter 5), the moisture content of pasture was set at 550% (dry basis) on 1 October and was allowed to decrease at the rate of 5% per day. The moisture content is also likely to vary during the day due to evapotranspiration but, because of lack of data, this effect was neglected in the present study.

4.4 Summary

A pasture growth model, written by Bowman (1985), was modified to predict the dry matter yield and digestibility of perennial pasture during the hay-making season. A 16-year series of historical weather data from Laverton, Victoria, was used to obtain weekly results. These data were then used to develop regression equations which could predict yield and digestibility.
Figure 4.4 Pasture growth curves during the hay-making season.
on a daily basis for the purpose of the hay-making simulation. A simple method was established to predict the moisture content of growing pasture on each day during the hay-making season.

In future research, emphasis should be given to developing a growth model such as that developed by Bowman but which can predict changes in yield and digestibility of pasture on a daily basis. Separate estimation of these parameters for leaves and stems, which will allow better estimation of mechanical losses during hay-making, is also desirable. Such a model should be able to estimate the pasture availability and soil moisture at the time of closing the paddocks, which were arbitrarily set for the present study. This will require a simulation of grazing policy during the rest of the year. The regrowth of pasture after harvesting varies depending upon the date of cutting, hence pasture which is harvested earlier would have higher yield of regrowth and vice versa. Therefore, provision should also be made to simulate the regrowth of pasture after cutting so that this effect could also be considered in a hay-making simulation. The model should also predict the moisture content of growing pasture depending on weather conditions; this would provide a better estimation of drying time at various stages of the season.
CHAPTER 5

SWATH HAY DRYING MODEL

The process of hay-making involves a period during which a cut crop is allowed to lose moisture naturally to the surrounding air; this process is termed field drying of hay. The time required to reduce the moisture of freshly cut crop to a level suitable for storage depends on meteorological factors, crop factors and management factors. These factors, particularly the meteorological ones, are normally highly variable during the drying period, a fact which results in large variation of drying time. Therefore, the modelling of the drying process is important in analysing hay-making systems.

In this chapter, the literature which is relevant to hay drying is first reviewed and then the drying model, to be used in the simulation to predict drying time for hay in the swath, is presented. The model for predicting changes in moisture content of baled hay is discussed in Chapter 6.

5.1 Hay Drying Process

If a hay crop is dried in the field, one may represent the drying and rewetting processes in a manner shown in Figure 5.1. The crop at the time of cutting is very wet and may contain about 400% moisture (dry basis). Soon after cutting the plants begin to lose moisture through the leaf pores (stomata), a process which
Figure 5.1 Typical changes in moisture content during field-drying of hay.
continues for 2-3 hours at the end of which time the stomata are almost closed (Jones and Palmer, 1932; Pederson and Buchele, 1960). During this period (a-b, Figure 5.1) the resistance to water loss is very low, resulting in rapid drying (Shepherd, 1964).

When stomata closure occurs about 40% of the water has already evaporated from the plants (Jones, 1939), and the water must then pass through the cuticle or waxy layer of the plant. The resistance to loss in this way is much higher than in the stomatal pathway (Shepherd, 1964) so that the drying rate during this period (b-c) is less than that in the initial period (a-b).

If dew forms during the night, the moisture content of crop increases, with a drier crop showing a greater increase (k-l) than the less dry crop (c-d). The moisture content may also decrease (i-j) during the night if the equilibrium moisture content of the hay is less than the actual moisture content (Kepner et al., 1960). If it rains during field drying of hay, the moisture content of the crop increases considerably (e-f).

The drying rate of a crop which has been made wet by rain or dew may be different from that of a non-wet crop. The initial drying rate of the crop after rewetting (for example, f-g) is normally higher than that during later periods (for example, g-h and h-i) mainly because the plants hold some surface water which offers no resistance to evaporation (Clark and McDonald, 1977).
5.2 The Drying Mechanism

The loss of moisture from the cut crop, i.e. evaporation, is a more complicated process than evaporation from growing vegetation, which itself is more complicated than evaporation from a water surface. Some brief remarks therefore need to be made about the basic evaporation process, as well as the additional aspects involved in the hay-drying process.

Evaporation from a wet surface has two necessary physical requirements. First, a source of heat is needed to cause the liquid water to vaporize. This source may be in radiant energy or in air blowing over the liquid. The second is for a diffusive process, by which water in the form of vapour is transferred from the underlying surface to the atmosphere by turbulence. This diffusion can proceed only in the presence of a gradient of concentration of water vapour from the evaporating surface to the overlying air.

It was this latter requirement which led to the first published work in evaporation studies by Dalton. Other studies followed this approach, but some investigations have also been based on the energy balance method. Rigorous studies using either of these two approaches require quite elaborate instrumentation to make measurements at more than one level over the evaporating surface.

To overcome this problem, Penman (1948) proposed a formula, based on sound physical principles, which combined these two approaches and allowed the use of standard meteorological measurements made
at one level only. His formula is:

\[ E = \frac{\Delta H + \gamma E_d}{\Delta + \gamma} \]  

(5.1)

where 
- \( E \) = evaporation, mm day\(^{-1}\)
- \( H \) = component due to available solar radiation, mm day\(^{-1}\)
- \( E_d \) = component due to wind speed and humidity effects, mm day\(^{-1}\)
- \( \Delta \) = slowly varying function of temperature, mb \(^{\circ}\)C\(^{-1}\)
- \( \gamma \) = psychrometric constant, mb \(^{\circ}\)C\(^{-1}\)

Because this formula makes use of atmospheric factors only, it applies either to evaporation from a water surface or from vegetation which is freely supplied with water; it is normally applied to periods of at least 24 hours. When soil-water is limiting, the plants close their stomata, which reduces the evaporation rate below that which the state of the atmosphere would require. In this situation complex measurements of the energy balance or of the aerodynamic diffusion are necessary to give accurate results. However, Monteith (1965) modified Penman's equation by introducing a "surface resistance", which can be empirically related to soil or plant moisture status.

In the case of hay drying, the evaporation of water from a cut crop proceeds against resistance, inside and outside the plant (Firth and Leshem, 1976; Jones and Harris, 1980). Inside the plant, the water has to leave the interior of cells via cell membranes and pass along the cell walls to eventually leave the plant via the stomata or cuticle. Thus, a stomatal or cuticular
resistance is offered to transfer of water vapour from within the plant tissue to the air immediately surrounding the plant within the swath.

Outside the plant, resistance is offered to the transfer of water vapour from the different layers of plants within the swath to the ambient air. A combination of these two resistances is called "swath resistance" (Clark and McDonald, 1967); this is likely to be related to the stage of drying and to swath structure.

The hay-drying process appears to have two stages. For the freshly cut material, while the stomata remain open, the drying rate depends mainly on atmospheric factors. However, the stomata progressively close, and the limiting factor is then the rate of diffusion of water through the partially dried material and through the cuticle. For constant environmental conditions, experiments show that the relation between plant moisture and time has two distinct slopes, with a fairly sharp discontinuity (Jones, 1979; Jones and Prickett, 1981). The initial rapid loss of moisture corresponds to the wet material with the stomata largely open; these then close, and the further slow rate of water loss corresponds to diffusion of water from the plant tissue to and through the cuticle. The first of these stages lasts for a period measured in hours rather than days (period a-b, Figure 5.1), so that the Penman (or Penman-Monteith) equation is difficult to apply. The second stage may be amenable to this approach, but a "swath resistance" may be required instead of a "surface resistance", an appropriate determination of which
presents problems.

5.3 Factors Affecting Drying Time of Hay

The numerous factors which affect the drying time of hay crops can be divided into three main categories:

(i) meteorological factors which include air temperature, relative humidity, wind speed, solar radiation, rainfall and dew;
(ii) crop factors which include crop species, maturity stage and yield; and
(iii) management factors which include conditioning, windrowing, raking and tedding.

5.3.1 Meteorological factors

The roles of temperature and relative humidity of the air are important during the drying process. Lower humidity combined with higher temperature during drying helps to reduce moisture content more quickly (Morris, 1972). However, vapour pressure deficit, the difference between the saturation vapour pressure and actual vapour pressure at the same temperature, has been recognised as a more useful single measure of the drying potential of the air because it takes into account both temperature and relative humidity (Hart and Burton, 1967; Spatz et al., 1970; Hill et al., 1977).

As the moisture diffuses from the drying crop into the atmosphere, the boundary layer at the crop-air interface becomes
saturated. This boundary layer must be removed and continually replaced by drier air if evaporation is to proceed. This movement of the air depends on wind and so the wind speed is also important in field drying process. For example, Mitchell and Shepperson (1955) considered that a wind speed of at least 8 km h⁻¹ is necessary to keep the air moving and to prevent the build up of local saturated atmosphere in the swath. Shepherd (1965) also found an increase in drying rate of grass with an increase in wind speed. However, he also observed that the effect of wind speed on drying rate decreased as the moisture content of grass decreased.

Higher radiation levels increase the temperature of the swath (Dernedde, 1980; Jones and Harris, 1980) which results in higher surface vapour pressure, especially during the early stages of drying when the material is wet. Hence, the effect of radiation in increasing the drying rate is more pronounced at higher moisture content than at lower moisture content (Hart and Burton, 1967).

Rain during the drying process results in an increase in moisture content which prolongs the overall drying time. A portion of rain water is absorbed by the plants and the remainder either drains away into the soil and/or stays as the surface water in the vicinity of the plants (Van Elderen, 1972). The drying rate of a crop after rewetting by rain is normally higher due to the presence of surface water (Clark and McDonald, 1977).
At night when relative humidities are higher and temperatures lower, dew increases the moisture content of the crop. The amount of water taken up by the crop at night as a result of dew may be very significant. Hart and Burton (1967) found that grass which had dried down to 23% moisture at the end of the day of cutting contained 24% moisture at the beginning of the third day of drying. Although no rain had fallen, this grass had taken up more water in the two nights after cutting than was removed in the drying on the second day. Thus, the uptake of moisture by hay should also be considered in a drying model.

5.3.2 Crop factors

Because of the difference in physiological characteristics of plants, the moisture content of a crop at a given stage of maturity and the ratio of leaf to stem vary among the species (Person and Sorenson, 1970; Jones and Prickett, 1981). Leaves dry faster than stems (Pederson and Buchele, 1960; Shepherd, 1964; Jones, 1979) and, therefore, leaf to stem ratio affects the overall drying rate of the crop.

Person and Sorenson (1970) compared several forage crops dried under controlled conditions. Alfalfa had the fastest drying rate, followed by kleingrass, coastal Bermuda grass and perennial sweet sorghgrass. Experiments conducted by Morris (1972) and Jones and Prickett (1981) also showed that the drying rate of crops varied between the species when dried under controlled conditions.
The moisture content of crop at a given physiological age not only varies from species to species but is also different at various growth stages for the same species. Mitchell and Shepperson (1955) noted in their field experiments that the moisture content of grass fell from 82% at pre-bloom stage to 70% (wet basis) at seed stage. Hart and Burton (1967) reported that moisture content of Bermuda grass decreased about 0.25% (wet basis) per day. Leaf to stem ratio also decreases as the crop matures, the proportion varying from 80% to 20% depending upon the stage of maturity (Green et al., 1971).

Jones (1979) found that young, leafy Italian ryegrass lost moisture much faster than mature grass when dried in a thin layer at 20 °C and 50% relative humidity. In field conditions, however, conflicting results have been found in regard to the effect of maturity stage on the drying rate. Field experiments conducted by Wilman and Owen (1982) showed that the drying rate of less mature crop was slightly higher than that of more mature crop, but Savoie et al. (1984) found that the mature grass lost water more quickly than the immature grass. Jones and Harris (1980) report that the drying time for grasses may even decrease after the ear emergence stage of growth because of the combined effect of less water to remove and faster drying rate of a stem due to its greater degree of exposure to a drying environment. There is also some evidence (Wilman and Owen, 1982) that an immature crop usually packs down more readily than a mature one, thus making the swath structure unfavourable for drying.
The yield of a crop also affects the drying rate. A higher yield increases the thickness of the swath which insulates the lower layers from radiation and impedes the diffusion of water vapour. The effect of yield on drying rate is more pronounced at higher moisture contents than at lower moisture contents (Hart and Burton, 1967; Wilman and Owen, 1982) because during the later stages of drying, the major resistance to water movement is inside the plant rather than outside it.

5.3.3 Management factors

There have been many attempts in the past to evolve new methods and machines to increase the drying rate of hay and make hay-making less hazardous to weather.

Mechanical conditioning treatments such as crushing and crimping open new pathways of water loss by physical rupture of plant tissues. Numerous studies (Jones and Palmer, 1932; Greenhill, 1959a; Kepner et al., 1960; Murdoch and Bara, 1963; Medling, 1964; Kurtz and Bilanski, 1968; Lievers and Feldman, 1975; Savoie et al., 1982, to mention only a few) have been carried out during the last five decades to investigate the effect of mechanical conditioning on the drying rate of hay. All these studies have confirmed that mechanical conditioning does increase the drying rate.

Chemical conditioning treatments facilitate water loss from the existing pathways by keeping the stomata open for a longer period and modifying the cuticle. Thermal conditioning treatments
are carried out by using heat which alters the plant's physical structure and reduces the cuticular resistance to water loss. Harris and Tullberg (1980) have reviewed in detail the studies related to chemical and thermal conditioning treatments. Most of these studies have been carried out in the laboratory and the true usefulness of these treatments in increasing the drying rate in the field has not been fully established.

Hay crops are normally dried in the swath but there are some machines, like windrowers, which discharge the material directly into a windrow. The main aim of such machines is to do all the pre-baling operations in one pass and thus eliminate the need for conditioners and rakes. Studies conducted by Goss et al. (1964); Kurtz and Bilanski (1967); Barrington and Bruhn (1970); and Lievers and Feldman (1975) have shown that the drying rate of hay in a windrow is less than the drying rate of hay in a swath.

When the crop is dried in an untouched swath, the upper layer dries faster than the lower layers (Clark and Mcdonald, 1977). Due to this the material in the upper layer develops a higher resistance to water movement than the material in the lower layers. Therefore, tedding or raking is normally carried out to create a favourable drying environment by rearranging the swath material. Both tedding (Medling, 1964) and raking (Savoie, 1982) have been found to increase the drying rate.
5.4 Models for Predicting Hay Drying Time

There have been different approaches in the past 15 years or so to develop mathematical models expressing relationships between drying rate and various factors.

5.4.1 Models based on thin-layer drying theory

If a thin layer (one particle deep) of an agricultural material is dried under controlled conditions, Equation 5.2, which assumes an exponential decay, can be used to determine its drying time (Hall, 1957).

\[
\frac{M - M_e}{M_0 - M_e} = e^{-kt} \tag{5.2}
\]

where \( M \) = moisture content at time \( t \), \% dry basis
\( M_e \) = equilibrium moisture content for drying conditions, \% dry basis
\( M_0 \) = original moisture content, \% dry basis
\( k \) = the drying constant for the material
\( t \) = the drying time, h

Based on the above thin-layer drying theory, some researchers have developed hay drying models of the following form:

\[
\frac{M - M_e}{M_0 - M_e} = e^{-kt^n} \tag{5.3}
\]

where \( n \) = material constant
Kemp et al. (1972) conducted laboratory studies to develop drying equations for alfalfa. Samples 10 cm deep were placed in drying chambers subjected to various levels of latent evaporation as measured with an atmometer. This instrument measures the combined effect of meteorological parameters such as temperature, relative humidity, wind speed and solar radiation. Different levels of latent evaporation were obtained by varying the dry bulb and wet bulb temperatures but keeping the radiation and wind speed constant in the drying chambers. The relationship between the drying constant, k, and latent evaporation was established for unconditioned alfalfa. It was found that the stage of maturity did not influence the drying rate and an identical equation was found for early and full bloom alfalfa.

Hill et al. (1977) also conducted laboratory experiments by placing alfalfa samples 2.5 cm deep in drying chambers with constant air flow but with various levels of air temperature and relative humidity. They established a relationship between the drying constant, k, and vapour pressure deficit considering it as a measure of the drying potential of the air.

Both the above models are incapable of predicting the actual field-drying time mainly because the effects of rain and dew, which are known to retard the drying of hay, are not considered. Also, the effects of radiation and wind speed are inadequately considered. In the field, radiation varies with time during the drying process. However, Hill et al. (1977) ignored this effect while Kemp et al. (1972), who took it into account, kept it constant for all their trials.
Realizing the limitations of these models, Savoie (1982) performed field experiments with alfalfa and developed a relationship between the drying constant, \( k \), and a number of factors such as temperature, radiation, yield and mechanical treatments. The wind speed was found to be a non-significant factor. He also proposed simple models for rain and dew absorption during the field drying process. The relative humidity, one of the important meteorological factors, was not considered as a factor affecting the value of the drying constant. The model also has the limitation in that it can only be used in areas where radiation data are available.

There are two major drawbacks in applying thin-layer drying theory to field-drying process of hay:

(i) The drying of hay in the field takes place in such a manner that every layer of a swath can be at a different moisture content after cutting (Firth and Leshem, 1976; Clark and McDonald, 1977). Therefore, it is possible that at any time after cutting, the top layer of swath might be in equilibrirum with the general surrounding atmosphere whereas the lower layers would still be losing moisture. Hence, the concept of equilibrium moisture can not be purely employed to the field drying of hay unless the swath is divided into several layers.

(ii) Equation 5.3 is best suited to drying of agricultural materials under constant environmental conditions where the equilibrium moisture content, \( M_e \), does not change. But \( M_e \) varies during the field-drying process because the meteorological factors are continuously changing. Thus to
use Equation 5.3 correctly, one needs to estimate $M_e$ every
time the meteorological conditions change. Erroneous results
can be obtained if a constant $M_e$ is used. As an illustration
of the changes in drying rate with different values of $M_e$, a
situation in which $M_o = 100\%$ (dry basis), $k = 0.2$ and $n = 1$,
will produce a drying rate of $16.3\% \, h^{-1}$ if $M_e = 10\%$ compared
with a rate of $10.9\% \, h^{-1}$ if $M_e$ is $40\%$.

5.4.2 Models based on "combination" method
of evaporation estimation

As discussed earlier, Penman (1948) developed a formula for
estimation of evaporation from a wet surface by combining "energy
balance" and "aerodynamic" approaches. Some researchers have used
Penman's approach to develop hay drying models.

The Bruck and Van Elderen model (1969) which included the effect
of rainfall and dew, simulated the drying of hay under field
conditions. The swath was divided into two layers and the change
in moisture content for each layer was determined after short
intervals of time during the simulation process.

Thompson (1981) modified the Penman-Monteith "combination"
equation (Monteith, 1965) to develop two drying models, viz. bulk
model and a multi-layer model. He used the concept of equilibrium
moisture content to allow the uptake of moisture by the swath
when the ambient humidity exceeds the equilibrium relative
humidity. An enormous amount of data is required to operate the
models, especially the multi-layer one. A major input to these
models is the swath resistance to moisture loss or uptake. The
swath resistance varies during drying and rewetting processes, and is not easy to determine.

The major limitation in using Penman's approach is that it requires radiation data which are not available for many meteorological stations.

5.4.3 Models based on regression analysis

Regression analysis has been widely used to establish relationships between the drying rate of hay and various factors.

Hart and Burton (1967) presented a drying model of coastal Bermuda grass based on the initial moisture content at the start of the day, vapour pressure deficit, solar radiation, and yield of the grass. In order to examine the effect of dew on moisture content, they divided the drying period into day (10.00 to 17.00 h) and night (17.00 to 10.00 h). The moisture content at the end of the night was found to be dependent upon moisture content at the beginning of the night, vapour pressure deficit during the night, and yield of grass.

This model does not include the effect of rain but the effect of dew is considered. However, the boundary between day and night is area specific. The time "10.00 h" in the morning was established as boundary between night and day assuming that surface water on grass due to dew would disappear by then. Such an assumption may not be true for all the days during a hay-making season, hence it would be more logical to also model the evaporation of water from
the surface of the grass.

Spatz et al. (1970) developed regression equations for drying which are of the form

\[ y = a e^{-bx} + cx^2 \] (5.4)

where \( y \) = moisture content,
\( x \) = independent variable measuring the effect of weather since cutting viz. accumulated hourly vapour pressure deficit, solar radiation or number of sunshine hours,
\( a, b, c \) = regression coefficients.

Equation 5.4 fitted their observed data best when accumulated vapour pressure deficit was considered as the independent variable. The effects of dew and rain were not considered in the model. However, a modified version of this model, which incorporated the effect of rainfall, was developed at National Institute of Agricultural Engineering, Silsoe, UK (Corrie and Parke, 1975).

Hayhoe and Jackson (1974) developed a model for the field drying of a crop containing a mixture of alfalfa and timothy. Estimated daily potential evaporation and recorded daily precipitation were correlated to experimental field drying data. Potential evaporation was estimated from daily meteorological data using an equation developed by Baier and Robertson (1965), and a conversion factor determined by Baier (1971). The model was specified by the following equation.
\[
\frac{M_n}{M_o} = \exp \left[ -a \sum_{i=1}^{n} (PE_i - bP_i) \right]
\] (5.5)

where

- \( M_n \) = moisture content observed at 16.30 h on the \( n \)th day after cutting, % wet basis
- \( M_o \) = original moisture content at the time of cutting, % wet basis
- \( PE_i \) = the estimated potential evaporation on the \( i \)th day after cutting, mm
- \( P_i \) = the precipitation on the \( i \)th day, mm
- \( a, b \) = constants

This model included the effect of rain but did not consider the effect of dew. The model also is not capable of predicting the moisture content at the beginning or any time during the day.

Using the concept introduced by Hayhoe and Jackson (1974), Hill (1976) proposed the following equation to predict the moisture content of the hay at the end of each day during rain-free drying.

\[
\frac{M_n}{M_o} = \exp \left[ -a \sum_{i=1}^{n} PE_i \right]
\] (5.6)

He defined "a" as a weighting factor characterising the hay material. Based on field experiments, values of "a" for crops like fescue, orchardgrass, bromegrass, alfalfa-timothy, and alfalfa-fescue were determined. Potential evaporation was estimated by an equation using maximum daily saturation vapour pressure deficit, average day-time wind speed, and total solar radiation. This model also did not take into account the effect
of rain and dew.

Kemp et al. (1977) related the moisture content of the drying crop to the cumulative latent evaporation with or without the cumulative rainfall. They modified the equation developed by Hayhoe and Jackson (1974), and expressed the relationships in the following forms.

\[
\frac{M}{M_0} = \exp \left( -a \, LE^b \right) \tag{5.7}
\]

\[
\frac{M}{M_0} = \exp \left( -c \, LE^d + e \, P^f \right) \tag{5.8}
\]

where \( M \) = moisture content at the end of a selected drying period, % dry basis

\( M_0 \) = original moisture content at the time of cutting, % dry basis

\( LE \) = the cumulative latent evaporation at the end of the selected drying period, ml

\( P \) = the cumulative precipitation at the end of the selected drying period, mm

\( a, b, c, d, e, f \) = constants

The above method of expressing the drying equations is superior to the methods of Hayhoe and Jackson (1974) and Hill (1976), because it allows the moisture content to be estimated at any time during the day rather than only at the end of the day. However, the comparative results of Equations 5.7 and 5.8 have shown that the effect of rainfall cannot be accurately described by using a single expression like Equation 5.8. Moreover, the
effect of dew was not considered in this model.

Dyer and Brown (1977) developed a computer model for drying hay in the field. They modified the expression (Equation 5.5) developed by Hayhoe and Jackson (1974) by rewriting it in a linear form. It was assumed that the change in moisture content during drying did not relate to stage of dryness when the moisture content was expressed on a wet weight basis. Rainfall and dew were included in the model.

The authors demonstrated the need to consider the effects of rainfall and dew on the drying time, but the model in its present form has an error and limitations. First, the effect of rain appears to have been considered twice in the model. Equation 5.5 developed by Hayhoe and Jackson (1974) included the effect of rainfall but the authors used a separate equation also to predict the increase in moisture content due to rain. Secondly, while determining the increase in moisture content at night an assumption was made that it occurred only when the relative humidity exceeded 90%. This assumption is not valid at all times because increase in moisture may result when the relative humidity is less than 90% (Hall, 1964).

Tullberg and Angus (1978) developed drying equations for alfalfa based on the laboratory studies. They expressed drying rate as a function of moisture content, vapour pressure deficit, leaf to stem ratio, and whether the alfalfa had been immersed in potassium carbonate solution or not. The usefulness of these equations in predicting field-drying time is doubtful because
these are based on drying data from very small samples (3-4 plants) which do not represent the swath structure found in the field. Also, no relationships have been presented to incorporate the effect of rainfall and dew.

5.5 Concluding Remarks on the Literature Review

Several factors affect the time required to reduce the moisture content of a freshly cut crop to that required for storage. Models with different parameters are required for different pasture crops because of their varying drying rates. The drying time of hay is largely dependent upon the meteorological factors and therefore, the effect of all these factors should be investigated while developing the model. The maturity stage of the crop does not significantly affect the drying time and therefore, this factor may be excluded. The yield has been found to affect the drying rate and therefore it should be considered in the model. Mechanical conditioning is another factor which should be included because of its proven effect in increasing the drying rate. Windrowing and tedding treatments should be taken into account if they are used for hay-making in the region. Again the effect of raking should be considered because it is essential in hay-making.

Drying models have been developed which simulate the moisture content of cut crop on "daily" as well as on "hourly" bases. To analyse hay-making systems more realistically estimation of moisture content at any given time during the day is desirable. The following specific conclusions are drawn from the review of
hay drying models:

(i) Thin-layer drying theory cannot adequately represent the field-drying process of hay, unless the swath is modelled as a sequence of separate inter-related layers.

(ii) The models based on the "combination" method of evaporation estimation require input data which are not readily available.

(iii) Regression analysis has been widely used in developing hay drying models. But the models developed so far have not adequately considered the effect of rain and dew. Moreover, many cannot estimate the moisture content at any time during a day.

Finally, from the review it is concluded that there are no published models which adequately simulate the drying of hay under field conditions.

5.6 Requirements of Hay Drying Model

Modelling of the hay drying process on an hourly basis is desirable from the standpoint of analysing hay-making systems more realistically. In the preceding sections, the literature regarding field drying of hay was reviewed and it was concluded that there was a need to develop an hourly drying model which could be operated with and without radiation data. In the following sections the field drying experiments and the drying model HAYDMO (HAY Drying MOdel) based on the field drying data are described.
The following guidelines were used in the development of HYDRO.

(i) The model should be able to predict drying time for unconditioned as well as conditioned hay.

(ii) The model should take into account the effect of rain and dew.

(iii) The model should be able to predict the moisture content at any time during a day.

(iv) The model should be able to operate with different meteorological parameters such as temperatures, wind speed and radiation.

5.7 Hay Drying Experiments

Field drying experiments were carried out during the hay-making season in 1983 at the Animal Research Institute in Werribee, Victoria. Twenty-four experiments, 12 each for unconditioned and conditioned treatments, were conducted with a perennial pasture comprised mainly of perennial ryegrass (Lolium perenne L.) and white clover (Trifolium repens L.). Experimental procedures and hay drying curves are described in the following sections.

5.7.1 Experimental procedures

5.7.1.1 Preparation of samples

Generally, on each day at 09.00 h, two swaths of pasture were cut with a New Holland sickle bar mower (Figure 5.2). On some occasions, cutting also was done in the afternoon, at 13.00 h, in order to have samples with different moisture contents drying
Figure 5.2 A sickle bar mower used during the field-drying experiments.

Figure 5.3 A conditioner used during the field-drying experiments.
under the same environmental conditions. Soon after cutting, one of the swaths was conditioned, using a New Holland conditioner (Figure 5.3).

Immediately after the conditioning operation, six samples, three each from unconditioned and conditioned pasture, were placed in rectangular trays. Each tray measured 1025 mm x 425 mm x 75 mm and was made of welded wire mesh, having square holes of 25 mm x 25 mm. The technique used in placing the sample was as follows. The empty tray was placed across the swath and the hay around its perimeter was cut with hand shears. The sample area under the tray was then lifted by means of two specifically constructed multi-pronged forks (Figure 5.4) and placed in the tray, with as little disturbance as possible (Figure 5.5). The tray and sample were then placed back in the swath (Figure 5.6).

5.7.1.2 Moisture determination

The trays were weighed at one hour intervals for the first four hours of drying on the day of cutting, and then at 2-3 hour intervals till 20.00 h. On the subsequent days, the weighing of trays began at 06.00 h. If rain occurred during drying, the trays were weighed after the rain for the purpose of determining increase in moisture due to rain. The trays were weighed using an Avery semi-self-indicating weighing balance, fitted with a special frame to hold the trays (Figure 5.7). The weighing was done in a temporary shed to avoid the effect of wind.

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Figure 5.4 Hand rakes used in lifting the sample.

Figure 5.5 Hand rakes beneath the sample area and ready for lifting.
Figure 5.6 A tray with sample lying in the swath.

Figure 5.7 The weighing balance with a special frame to hold the tray during weighing.
Towards the end of the drying period, a raking operation was simulated by inversion of the sample. For this purpose, an empty tray was placed over the top of a tray with a sample and the pair quickly inverted. The second tray was then placed back to the original position in the swath. The samples were weighed just before the raking operation and measurements were continued till the end of drying.

At the end of the drying cycle, the material from each tray was put into paper bags and then transferred to the laboratory for dry matter determinations using the oven method (Greenhill, 1960). Moisture content at each observation time was then calculated from the dry matter weight and the weights of the samples which had been taken during the field-drying process.

5.7.1.3 Recording weather data

An automatic portable weather station developed and described by Watts (1983) was set up near the test field to record meteorological parameters. The data collected were:

(i) Dry bulb temperature
(ii) Wet bulb temperature
(iii) Wind speed
(iv) Global radiation

Dry and wet bulb temperatures were recorded using a Bowen ratio system (Figure 5.8). This system measures the temperatures at two heights (1 m and 2 m) alternatively every 15 minutes. The average of these values was taken as a temperature reading at every half
Figure 5.8 Bowen ratio system with temperature sensors.

Figure 5.9 Cup anemometer mounted on a mast.
an hour. A cup anemometer (Figure 5.9) was used to record the wind run and global radiation was recorded using a pyranometer (Figure 5.10). A data logger (Figure 5.11) continuously integrated the outputs from each sensor and punched the data on to paper-tape at 15 minute intervals.

Some meteorological parameters were recorded manually during the experimental period, with a view to using them if the automatic weather station failed to give reliable data. Dry and wet bulb temperatures were noted down every hour during the day time (06.00 to 20.00 h) using dry and wet bulb thermometers placed in a Stevenson screen near the site (Figure 5.10). Minimum and maximum temperatures were also recorded for each day during the experimental period. A standard rain gauge was installed in the field to measure the rainfall.

5.7.2 Drying Curves

Drying curves were plotted from the data of all the 24 experiments. As an example, the curves for two experiments are presented (Figure 5.12) to show how the moisture content of unconditioned and conditioned hay changed in the field conditions. The weather data taken during the two experiments are also shown in this figure.

It is clear from Figure 5.12 that during the first 3–4 hours of drying, plant moisture is lost very rapidly which confirms the results of others as shown in Section 5.1. By noting the general slopes of the drying curves and by inspecting minimum daily
Figure 5.10  (a) Radiation mast with a pyranometer.  
(b) Stevenson screen which housed dry bulb, wet bulb, minimum and maximum thermometers.

Figure 5.11  Data logger.
Figure 5.12 Drying curves for unconditioned and conditioned hay.
moisture contents, it is clear that the conditioned hay dried more rapidly than the unconditioned hay. Figure 5.12 suggests that under favourable weather conditions it would have been possible to bale the conditioned hay on the day after cutting. Unconditioned hay would have normally required an extra day before it could be baled.

The moisture uptake during the night was largely dependent upon the weather conditions during that time. As shown in Figure 5.12, the gain in moisture of unconditioned hay was almost negligible on the night of 21 November because of high temperatures. However, on the night of 22 November, when the temperatures were lower, the moisture content increased by more than 40%.

5.8 Basic Structure of the Model

It appears from Figure 5.12 that the drying curves during field-drying of hay are of a saw-toothed appearance mainly because of rewetting which occurs during the drying process. In order to represent such drying curves numerically, the following basic equations were developed to predict the moisture content of hay at any given time after cutting.

\[
M_{m,n} = M_0 + \sum_{j=1}^{n} C_{m,j}, \quad \text{for } m=1 \quad (5.9)
\]

\[
M_{m,n} = M_0 + \sum_{i=1}^{m-1} C_{M,i} + \sum_{i=1}^{m-1} C_{M,i} + \sum_{j=1}^{n} C_{M,j}, \quad \text{for } m>1 \quad (5.10)
\]
where \( M_{m,n} \) = moisture content at the end of \( n^{th} \) hour on the \( m^{th} \) day after cutting, % dry basis

\( M_0 \) = original moisture content at the time of cutting, % dry basis

\( CMD_i \) = change in moisture content during the \( i^{th} \) day after cutting, % dry basis

\( CMN_i \) = change in moisture content during the \( i^{th} \) night after cutting, % dry basis

\( CM_{m,j} \) = change in moisture content during the \( j^{th} \) hour on the \( m^{th} \) day after cutting, % dry basis

For clarity it was reiterated that "day" is defined to be from 06.00 to 20.00 h and "night" from 20.00 to 06.00 h. Day 1 is the day of cutting and \( n^{th} \) hour on day 1 is defined to be the \( n^{th} \) hour after cutting. On any subsequent day the \( n^{th} \) hour is defined to be \( n^{th} \) hour after 06.00 h. A positive value of change in moisture content represents an increase in moisture content and a negative value represents a decrease.

5.9 Transformation of Drying Data

Drying data collected during the field experiments were transformed into a form suitable for developing the model. The reduced data are given in Appendix D.

Dry and wet bulb temperatures were used to calculate the vapour pressure deficit at the beginning and end of each hour, and the mean vapour pressure deficit for each hour was calculated by averaging these values. Vapour pressure deficit is the
difference between the saturated vapour pressure and actual vapour pressure. Equation 5.11 developed by Lowe (1977) is used to calculate saturated vapour pressure for each recorded temperature.

\[ P_s = \sum_{k=0}^{6} a_k T^k \]  \hspace{1cm} (5.11)

where \( P_s \) = saturated vapour pressure, mb
\( T \) = temperature, °C
\( a_0 = 6.10 \)
\( a_1 = 4.43 \times 10^{-1} \)
\( a_2 = 1.42 \times 10^{-2} \)
\( a_3 = 2.65 \times 10^{-4} \)
\( a_4 = 3.03 \times 10^{-6} \)
\( a_5 = 2.03 \times 10^{-8} \)
\( a_6 = 6.13 \times 10^{-11} \)

The saturated vapour pressure values (mb) were converted to SI units (kPa). The actual vapour pressure was calculated using the method proposed in ASAE (1980).

During part of the experimental period, the Bowen ratio system developed a fault and thus gave incorrect readings for temperatures. In view of this, the manually recorded temperatures were used to calculate the vapour pressure deficit for each hour during the day (06.00 to 20.00 h). The average hourly vapour pressure deficit during the night (20.00 to 06.00 h) was calculated, based on the hourly temperature data collected from a nearby meteorological station, Laverton, which is situated about 5 km away from the experimental site. The area between the two sites is flat and the minimum temperatures recorded at both the sites compared well with each other.
The wind speed and radiation data collected at the experimental site were comparable with the data collected at the meteorological station which confirmed that these data were correctly recorded through the automatic weather station.

5.10 Statistical Analysis of Drying Data

The multiple regression analysis subprogram available in the SPSSX package (Noursis, 1983) was used to analyse the data. A step-wise regression was used to delete the non-significant variables at the 0.05 level of significance for all the equations. The values in Table 5.1 show the range of variability in the pasture, and in the weather conditions encountered during the drying experiments. The following sections describe the various equations developed for use in the drying model.

5.10.1 Estimation of change in moisture content during the day

The change in moisture content during the $i^{th}$ day ($CMD_i$) can be determined using the following equation:

$$CMD_i = \sum_{j=1}^{L} CM_{i,j}$$  \hspace{1cm} (5.12)

where $CM_{i,j}$ = change in moisture content during $j^{th}$ hour on the $i^{th}$ day after cutting, % dry basis

$L$ = length of the day (sunrise to sunset), h
Table 5.1 Variability of pasture and weather during the drying experiments.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pasture:</strong></td>
<td></td>
</tr>
<tr>
<td>Initial moisture content, % dry basis</td>
<td>233 - 407</td>
</tr>
<tr>
<td>Yield (dry matter), t ha(^{-1})</td>
<td>3.4 - 6.0</td>
</tr>
<tr>
<td><strong>Weather:</strong></td>
<td></td>
</tr>
<tr>
<td>Hourly mean vapour pressure deficit during the day (06.00 to 20.00 h), kPa</td>
<td>0.11 - 2.69</td>
</tr>
<tr>
<td>Mean vapour pressure deficit during the night (20.00 to 06.00 h), kPa</td>
<td>0.08 - 0.73</td>
</tr>
<tr>
<td>Hourly global radiation, MJ m(^{-2})</td>
<td>0.20 - 3.82</td>
</tr>
<tr>
<td>Wind speed, m s(^{-1})</td>
<td>1.0 - 13.3</td>
</tr>
<tr>
<td>Maximum daily temperature, °C</td>
<td>12.0 - 30.0</td>
</tr>
<tr>
<td>Minimum daily temperature, °C</td>
<td>4.5 - 18.0</td>
</tr>
<tr>
<td>Rain during a wet spell, mm</td>
<td>0.5 - 29.0</td>
</tr>
</tbody>
</table>

Any given hour during the day could be either rain-free or rainy. Thus, there is a need to develop the relationship for \(CM_{i,j}\) for both cases.

The drying crop may have either original plant water or that absorbed due to rewetting after rain or dew. Therefore, the drying data was separated into these two main categories and two sets of equations were developed to estimate \(CM_{i,j}\) during a rain-free hour. The effect of several factors on change in moisture content was investigated. These factors were:

(i) moisture content at the beginning of the hour
(ii) vapour pressure deficit during the hour
(iii) wind speed during the hour
(iv) global radiation during the hour
(v) yield of pasture
(vi) conditioning factor distinguishing between conditioned and unconditioned hay
(vii) raking factor distinguishing between raked and unraked hay

A variety of linear and curvilinear functions were investigated as potential forms for empirical relationships between $CM_{i,j}$ and the above factors. Multiplicative power functions of the following type were found to give the best fit to the data.

$$ y = a_0 \prod_{k=1}^{n} x_k^{a_k} $$

(5.13)

A number of equations were developed for the estimation of $CM_{i,j}$ by using different combinations of weather variables. Table 5.2 (Equations 5.14 - 5.16) and Table 5.3 (Equations 5.17 and 5.18) give the results of multiple regression analysis for original plant water and rain/dew water respectively. The description of the symbols used in above tables is as follows:

$M_{i,j-1}$ = moisture content at the end of $(j-1)^{th}$ hour on the $i^{th}$ day after cutting, % dry basis

$MVP_{i,j}$ = mean vapour pressure deficit during $j^{th}$ hour on the $i^{th}$ day after cutting, kPa

$W_{i,j}$ = wind speed during $j^{th}$ hour on the $i^{th}$ day after cutting, m s$^{-1}$

$RG_{i,j}$ = global radiation during $j^{th}$ hour on the $i^{th}$ day after cutting, MJ m$^{-2}$

COND = conditioning dummy variable, its value is 0 for
unconditioned hay and 1 for conditioned hay

RK  = raking dummy variable, its value is 0 for unraked hay and 1 for raked hay

R^2  = multiple coefficient of determination

SE  = standard error of estimate

N  = number of observations

Table 5.2 Multiple regression analysis of \( CM_{i,j} \) with various independent variables (hay having plant water only).

| Equation | Variable | Regression Coefficient | Constant | \( R^2 \) | SE | N |
|----------|----------|-------------------------|----------|-----------|----|--|---|
| 5.14     | \( M_{i,j-1} \) | 1.50                    | -0.0069  | 0.86      | 7.8 | 185 |
|          | MVPDi,j  | 0.46                    |          |           |     |    |
|          | (1+COND) | 0.43                    |          |           |     |    |
|          | (1+RK)   | 0.82                    |          |           |     |    |
| 5.15     | \( M_{i,j-1} \) | 1.58                    | -0.0031  | 0.92      | 5.6 | 185 |
|          | MVPDi,j  | 0.33                    |          |           |     |    |
|          | RG\( i,j \) | 0.50                    |          |           |     |    |
|          | (1+COND) | 0.45                    |          |           |     |    |
|          | (1+RK)   | 0.93                    |          |           |     |    |
| 5.16     | \( M_{i,j-1} \) | 1.56                    | -0.0027  | 0.93      | 5.4 | 185 |
|          | MVPDi,j  | 0.29                    |          |           |     |    |
|          | RG\( i,j \) | 0.56                    |          |           |     |    |
|          | Wi\( i,j \) | 0.14                    |          |           |     |    |
|          | (1+COND) | 0.44                    |          |           |     |    |
|          | (1+RK)   | 0.91                    |          |           |     |    |
Table 5.3 Multiple regression analysis of \( \text{CM}_{i,j} \) with various independent variables (hay having rain or dew water also).

<table>
<thead>
<tr>
<th>Equation</th>
<th>Variable</th>
<th>Regression Coefficient</th>
<th>Constant</th>
<th>( R^2 )</th>
<th>SE</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.17</td>
<td>( M_{i,j-1} )</td>
<td>1.14</td>
<td>-0.0529</td>
<td>0.76</td>
<td>9.5</td>
<td>131</td>
</tr>
<tr>
<td></td>
<td>MVPDI( _{i,j} )</td>
<td>0.27</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(1+COND)</td>
<td>0.28</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.18</td>
<td>( M_{i,j-1} )</td>
<td>1.02</td>
<td>-0.0767</td>
<td>0.83</td>
<td>7.9</td>
<td>131</td>
</tr>
<tr>
<td></td>
<td>RG( _{i,j} )</td>
<td>0.38</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(1+CCND)</td>
<td>0.22</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The drying rate \( \left( \text{CM}_{i,j} \right) \) was significantly affected by all but one factor, viz. the yield of pasture. This was in apparent contradiction of the results obtained by Hart and Burton (1967), who found that moisture content at the end of the day was significantly affected by the yield of crop. However, the experiments performed by them covered a large range of yield \( (0.43 - 13.82 \text{ t ha}^{-1}) \) which would have contributed towards its significance in the drying equation. The present study has investigated the yield range of only 3.4 - 6.0 \text{ t ha}^{-1}.

Of all the weather variables, the contribution of wind speed in predicting the drying rate is relatively low. When included, the increase in \( R^2 \) and decrease in SE values were very small as is evident from the comparison of their values for Equations 5.15 and 5.16. The wind speed was also found to be a non-significant variable when the hay contained rain or dew water (Table 5.3). The vapour pressure deficit was found to be a non-significant
variable in the presence of radiation when hay contained rain/dew water also.

The analysis suggests that the drying rate, % moisture content per hour, of conditioned hay was about 35% higher than that of the unconditioned hay when the crop contained original plant water only. This figure dropped to about 20% when the crop contained rain or dew water also. This change is due to the fact that the wet crop contained some surface water, which probably evaporated at about the same rate irrespective of the treatment and this lowered the overall per cent increase in drying rate of conditioned hay.

During the field-drying experiments, there were several occurrences of rain. A simple non-linear model (Equation 5.19) was developed to determine the increase in moisture content due to rain.

\[
CM_{i,j} = 131.8 R^{0.29}_{i,j} (1 + \text{COND})^{0.27}
\]

\(R^2 = 0.86, \ SE = 33.4, \ N = 21\)

where, \(R_{i,j}\) = rainfall during \(j^{th}\) hour on the \(i^{th}\) day after cutting, mm

Moisture content at the beginning of rainfall was found to be a non-significant variable. However, the conditioned hay absorbed more moisture than the unconditioned hay for the same amount of rain. The model suggests that moisture content does not increase at the same rate for unconditioned and conditioned hay as the
amount of rainfall increases. The model also suggests if there is a continuous rainfall of more than one hour, then the rainfall during that period should be accumulated and the change in moisture content for the whole period should be calculated, using Equation 5.19.

5.10.2 Estimation of change in moisture content during the night

Any given night (sunset to sunrise) during the field-drying process could be either rainy or rain-free. Hence, two separate equations are also needed to predict the change in moisture content.

The effects of the following factors on change in moisture content during a rain-free night were investigated:

(i) moisture content at the end of the day
(ii) average vapour pressure deficit during the night
(iii) average wind speed during the night
(iv) yield of pasture
(v) conditioning

A number of relationships were tried and linear equations of the following type were found to give the best fit to the data.

\[ y = a_0 + \sum_{k=1}^{n} a_k x_k \]  

(5.20)

Table 5.4 (Equations 5.21 and 5.22) gives the results of multiple regression analysis of change in moisture content during the ith night (CMNi) with various independent variables. The description
of the symbols used is as follows:

\[ ME_i \] \text{ moisture content at the end of } i^{th} \text{ day after cutting, } \% \text{ dry basis} \\
\[ VPDN_i \] \text{ average hourly vapour pressure deficit during the } i^{th} \text{ night after cutting, kPa} \\
\[ Y \] \text{ yield (dry matter) of pasture, t ha}^{-1}

<table>
<thead>
<tr>
<th>Equation</th>
<th>Variable</th>
<th>Regression Coefficient</th>
<th>Constant</th>
<th>( R^2 )</th>
<th>SE</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.21 [ ME_i ]</td>
<td>-0.15</td>
<td>68.7</td>
<td>0.79</td>
<td>9.4</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>[ VPDN_i ]</td>
<td>-81.73</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.22 [ ME_i ]</td>
<td>-0.14</td>
<td>107.8</td>
<td>0.85</td>
<td>7.9</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>[ VPDN_i ]</td>
<td>-83.58</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[ Y ]</td>
<td>-8.47</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The model suggests that moisture content during a rain-free night could also decrease if the moisture content at the beginning of night and/or vapour pressure deficit during the night are sufficiently high. Swaths having higher yields would result in smaller increases in moisture content compared to the swaths having lower yields. This was also evident during the experiments where it was found that only the upper layers absorbed the moisture resulting in a smaller overall increase in moisture content of swaths having greater thickness. No significant difference was found between conditioned and unconditioned hay; wind speed was also found to be a non-significant variable.
For a rainy night, Equation 5.23 can be used to predict the increase in moisture content due to rainfall. This equation is essentially the same as Equation 5.19 but $R_{i,j}$ is replaced by $RN_i$.

$$CMN_i = 131.8 RN_i^{3.29} (1+COND)^{0.27}$$  (5.23)

where $RN_i =$ rainfall during the $i^{th}$ night after cutting, mm

5.11 Development of a Computer Program (HAYDMO)

A computer program HAYDMO (HAY Drying MOdel) was written in FORTRAN 77 to simulate the moisture content of hay after cutting. The program logic is shown in Figure 5.13. The weather input data required are given below:

(i) hourly mean vapour pressure deficit, kPa  (06.00 to 20.00 h)
(ii) hourly wind speed, m s$^{-1}$  (06.00 to 20.00 h)
(iii) hourly global radiation, MJ m$^{-2}$  (06.00 to 20.00 h)
(iv) hourly rainfall, mm  (06.00 to 20.00 h)
(v) average hourly vapour pressure deficit during the night, kPa  (20.00 to 06.00 h)
(vi) rainfall during the night, mm  (20.00 to 06.00 h)

The model can be operated without data items (ii) and (iii) by selecting appropriate drying equations from Tables 5.2 and 5.3. Hence, the estimation of drying time is also possible in those areas where radiation data are not available.
Figure 5.13 Flow chart of hay drying model (HAYDMO).
5.12 Testing of HAYDMO

The drying data of 22 experiments were used to develop the regression equations described earlier. The remaining data of two experiments were used to test the performance of the model. The computer program HAYDMO was used to simulate the drying process using weather data for these experiments. Figures 5.14 and 5.15 show the predicted drying curves and the observed data for these experiments.

The comparison of observed and predicted moisture contents reveals that the model is able to simulate the saw-toothed type of drying curves normally expected during field-drying of hay. The model shows good sensitivity to both the type of hay and the change in drying conditions. The comparison of predicted and observed moisture contents at the point of maximum rewetting suggests that the increase in moisture content due to rain is predicted quite satisfactorily by Equation 5.19.

In general, there is a close agreement between the observed and predicted moisture contents. The model appears to predict the moisture contents more accurately during the early periods of drying compared to the later. The reason could be that fewer data in the lower moisture content range were available which could have caused the model to be less accurate in predicting the moisture content in that range. Also, some errors could have arisen due to the inability of the weighing system to record the small changes in weight which occur during the later periods of drying. However, the model seems to be sufficiently accurate for...
Figure 5.14 Predicted and observed moisture contents of unconditioned hay.
Figure 5.15 Predicted and observed moisture contents of conditioned hay.
use in studies relating to decision making problems such as simulation of hay-making systems.

5.13 Summary

The hay drying model developed can adequately simulate the drying and rewetting processes occurring during field-drying of hay. A non-linear model is used to relate the drying rate during daytime to weather and management factors. The hay which has been wet dries differently from hay which has not and hence two sets of equations are developed, one for the hay having original plant water only and the other for the hay having rain/dew water also. Statistical analysis of the drying data reveals that the drying rate is mainly a function of moisture content of the hay, vapour pressure deficit, global radiation and machinery treatments. The effect of wind speed is small compared to other meteorological factors. Some past studies have found that the drying rate is affected by yield of hay, but in this work, the effect of the small yield range on drying rate has been found non-significant. Two simple models are also developed to simulate the rewetting process of hay, either due to rain or dew.

During the field drying experiments, raking operation was simulated by inversion of sample in the trays. It is recommended that a separate drying model for raked hay should be developed by performing actual raking operations in the field at different times during the drying cycle. Such a model would be helpful in assessing the effects of early raking on the performance of hay-making systems.
CHAPTER 6

BALED HAY DRYING MODEL

The model for predicting changes in moisture content of cut crop lying in the swath up to the baling stage was described in Chapter 5. Hay is frequently not carted to the store immediately after baling mainly due to shortage of labour. Such hay may be wet by rain and thus go through several wetting and drying cycles before its moisture content finally becomes suitable for safe storage. Therefore, a drying model is required which could simulate the changes in moisture content of hay from the time it is baled to the time it is put into storage.

Greenhill (1957) carried out some experiments to investigate the effect of weather on moisture changes in hay bales left out in the field under different arrangements. However, his results could not be used because the data were collected at an interval ranging from 1-11 days and also the corresponding detailed weather information was not available. No other experimental data were found in the literature that could be useful for developing a drying model. In this chapter, a baled hay drying model and an experiment on which it was based are described.

6.1 Drying Experiment

A drying experiment was carried out during the hay-making season in 1985. Eighteen bales of hay comprised mainly of ryegrass and
white clover were used for this experiment. The experimental procedure and the drying data are described in the following sections.

6.1.1 Experimental procedure

At the start of experiment, grab samples from each bale were placed into paper bags and then transferred to the laboratory for determination of moisture content using the oven method (Greenhill, 1960). The bales were then weighed by using a platform scale and placed in the field as shown in Figure 6.1. Different quantities of water were applied on the bales using a watering can. The bales were weighed soon after the application of water and again at 2-6 hour intervals on subsequent days.

The weather parameters, dry and wet bulb temperatures, were recorded every hour during the day using dry and wet bulb thermometers in a Stevenson screen placed nearby (Figure 6.2).

6.1.2 Drying data

The dry matter weight of each bale was determined using the initial moisture content of hay and its weight before applying rain. For every bale, the moisture content at each observation time was then calculated from its dry matter weight and weights which had been taken during the drying process. Dry and wet bulb temperatures were used to calculate the mean vapour pressure deficit for each hour by the same method as described in Section 5.9. The reduced data are given in Appendix E. The values in
Figure 6.1 The general lay-out of bales and platform scale used in the experiment.

Figure 6.2 Stevenson screen which housed dry and wet bulb thermometers.
Table 6.1 show the range of variability of hay and weather during the experiment.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial weight of bales, kg</td>
<td>21.8 - 27.8</td>
</tr>
<tr>
<td>Dry matter weight of bales, kg</td>
<td>19.0 - 24.3</td>
</tr>
<tr>
<td>Initial moisture content of bales, % dry basis</td>
<td>13.4 - 14.5</td>
</tr>
<tr>
<td>Moisture content of bales after the application of water, % dry basis</td>
<td>38.9 - 93.5</td>
</tr>
<tr>
<td>Hourly mean vapour pressure deficit, kPa</td>
<td>0.4 - 2.0</td>
</tr>
</tbody>
</table>

6.2 Basic Structure of the Model

The following basic equations, similar to the ones described in Section 5.8, were used to predict the moisture content of baled hay at any given time after baling.

\[
M_{m,n} = M_b + \sum_{j=1}^{n} C_{M, j}, \quad \text{for } m = 1 \quad (6.1)
\]

\[
M_{m,n} = M_b + \sum_{i=1}^{m-1} CMD_i + \sum_{i=1}^{m-1} \sum_{j=1}^{n} CM_{i,j}, \quad \text{for } m > 1 \quad (6.2)
\]

where \(M_{m,n}\) = moisture content at the end of \(n^{th}\) hour on the \(m^{th}\) day after baling, % dry basis

\(M_b\) = moisture content at the time of baling, % dry basis

\(CMD_i\) = change in moisture content during the \(i^{th}\) day
after baling, % dry basis

$\text{CM}_i = \text{change in moisture content during the } i^{\text{th}} \text{ night after baling, } % \text{ dry basis}$

$\text{CM}_{m,j} = \text{change in moisture content during the } j^{\text{th}} \text{ hour on the } m^{\text{th}} \text{ day after baling, } % \text{ dry basis}$

Again, as before "day" is defined to be from 06.00 to 20.00 h and "night" from 20.00 to 06.00 h. Day $l$ is the day of baling and $n^{\text{th}}$ hour on day $l$ is defined to be the $n^{\text{th}}$ hour after baling. On any subsequent day the $n^{\text{th}}$ hour is defined to be $n^{\text{th}}$ hour after 06.00 h. A positive value of change in moisture content represents an increase in moisture content and a negative value represents a decrease.

### 6.2.1 Estimation of change in moisture content during the day

The change in moisture content during the $i^{\text{th}}$ day ($\text{CMD}_i$) can be determined using the following equation:

$$\text{CMD}_i = \sum_{j=1}^{L} \text{CM}_{i,j}$$  \hspace{1cm} (6.3)

where $\text{CM}_{i,j} = \text{change in moisture content during } j^{\text{th}} \text{ hour on the } i^{\text{th}} \text{ day after baling, } % \text{ dry basis}$

$L = \text{length of the day (sunrise to sunset), h}$

Any given hour during the day could be either rain-free or rainy. Thus, there is a need to develop the relationship for $\text{CM}_{i,j}$ for both cases.
6.2.1.1 Change in moisture content during a rain-free hour

The drying data given in Appendix E were analysed using a multiple regression analysis subprogram available in the SPSS package (Noursis, 1983). A step-wise regression was used to delete the non-significant variables at the 0.05 level of significance.

The effect of two factors, moisture content at the beginning of the hour and mean vapour pressure deficit during the hour, on change in moisture content was investigated. A variety of linear and curvilinear equations were tried and Equation 6.4 was found to give the best fit to the data. Due to lack of data, this equation was also used to predict the change in moisture content when the bales contained original plant water only.

\[
CM_{i,j} = -0.023 M_{i,j-1}^{0.87} MVPD_{i,j}^{0.31}
\]

\[(R^2 = 0.36, SE = 0.35, N = 108)\]

where 
\(M_{i,j-1}\) = moisture content at the end of \(j-1^{th}\) hour on the \(i^{th}\) day after baling, \% dry basis

\(MVPD_{i,j}\) = mean vapour pressure deficit during \(j^{th}\) hour on the \(i^{th}\) day after baling, kPa

\(R^2\) = multiple coefficient of determination

\(SE\) = standard error of estimate

\(N\) = number of observations
6.2.1.2 Change in moisture content during a rainy hour

No experimental data were collected to develop a model for determining the increase in moisture content due to the application of various amounts of rain. The experimental data reported in Section 6.1.1 could not be used as the amount of water shedding of the bales was not measured. Moreover, water application by the watering can did not simulate the rain very well. However, based on a theoretical analysis (Appendix F), Equation 6.5 was developed for this purpose. This equation is based on the assumption that 80% of rain falling on the bales is absorbed and the remaining proportion sheds from the sides (Corrie and Parke, 1975).

\[ CM_{i,j} = 2.0 \times R_{i,j} \]  

(6.5)

where, \( R_{i,j} \) = rainfall during \( j^{th} \) hour on the \( i^{th} \) day after baling, mm

6.2.2 Estimation of change in moisture content during the night

Any given night (sunset to sunrise) during the field-drying process could be either rainy or rain-free. Unlike hay in the swath, the change in moisture content of a bale due to dew is likely to be very small and thus \( CMN_i \) during a rain-free night was neglected. However, for a rainy night, Equation 6.6 can be used to predict the increase in moisture content due to rainfall. This equation is essentially the same as Equation 6.5 but \( R_{i,j} \) is replaced by \( RN_i \).
\[ \text{CMN}_i = 2.0 \text{ RN}_i \quad (6.6) \]

where \( \text{RN}_i \) = rainfall during the \( i^{th} \) night after baling, mm

6.3 Summary

A simple model was developed to estimate the change in moisture content of hay after the baling operation. The model is admittedly approximate and would benefit from further investigation. In the model, only mean vapour pressure deficit was considered as a weather parameter affecting the drying rate. Further experiments should be conducted to include other parameters such as radiation and wind speed. Increase in moisture content due to rain was determined theoretically and thus experiments are needed to check the validity of this assumption. The model presented is valid for only rectangular bales and a similar model should also be developed for large round bales.
CHAPTER 7

HAY LOSS MODEL

In order to compare the performance of different hay-making systems and management policies, it is essential to estimate the net digestible dry matter (NDDM) yield of harvested hay. Both quantitative and qualitative losses which occur during the various stages of hay-making can be classified as follows:

(i) physical loss of plant material, especially leaves, due to the use of various machines,
(ii) loss of dry matter due to the respiration of the cut crop, and
(iii) loss of soluble nutrients by leaching during periods of rain.

In this chapter methods are presented to estimate these losses, based on the available literature.

7.1 Net Digestible Dry Matter

Dry matter yield and digestibility of standing pasture are determined using the pasture growth model described in Chapter 4. Now, if $a_1, a_2, \ldots a_n$ represent the fractional losses of dry matter due to various factors, then the net dry matter yield of harvested hay can be expressed as follows:

$$NDM = DM \prod_{i=1}^{n} (1 - a_i)$$  \hspace{1cm} (7.1)
where \( \text{NDM} \) = net dry matter yield of hay, \( t \text{ ha}^{-1} \)

\( \text{DM} \) = dry matter yield of standing pasture, \( t \text{ ha}^{-1} \)

Similarly, if \( b_1, b_2, \ldots, b_n \) represent the fractional losses of digestibility due to various factors, then the net digestibility after harvesting is simply

\[
\text{ND} = \text{D} \prod_{i=1}^{n} (1 - b_i) \tag{7.2}
\]

where \( \text{ND} \) = net digestibility of hay

\( \text{D} \) = digestibility of standing pasture

Then the \( \text{NDDM} \) can be determined as follows:

\[
\text{NDDM} = \text{NDM} \times \text{ND} \tag{7.3}
\]

The following sections consider the important factors that affect losses at each stage of hay-making.

7.2 Dry Matter Losses During Cutting

During cutting small portions of plants, mainly leaves, become detached and subsequently cannot be raked and baled. The cutting operation is performed by many different machines and the extent of losses depends upon the type of machine used. These machines can be grouped into two categories:

(i) mowers, and

(ii) mower-conditioners.
Because much of the information available on cutting loss is for lucerne, and little for pasture hay, in this thesis lucerne data are used to arrive at an average loss value for pasture. Losses for mower-conditioners are generally higher than mowers because of the harsh treatment given to the plant by the conditioners. In Table 7.1 the range of cutting losses determined by various research workers, is set out.

<table>
<thead>
<tr>
<th>No.</th>
<th>Losses during cutting (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mower</td>
<td>mower-conditioner</td>
</tr>
<tr>
<td>1</td>
<td>1.0</td>
<td>2.1 - 4.6</td>
</tr>
<tr>
<td>2</td>
<td>&lt;1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>3</td>
<td>2.0</td>
<td>3.0 - 4.0</td>
</tr>
<tr>
<td>4</td>
<td>0.2 - 1.0</td>
<td>0.2 - 1.0</td>
</tr>
</tbody>
</table>

There seems to be little agreement for cutting losses as revealed by the review of above studies; a cause of the variation could be related to crop condition and machine adjustments. Based on above results dry matter loss of 1% for mowers and 2% for mower-conditioners were assumed in this project.

The above loss does not include stubble loss which depends upon the height of cut; this may vary with the type of machine. However, this loss was not considered because no information was available.
7.3 Dry Matter Losses During Drying

During the field-drying process, plant respiration and rainfall are known to alter the quantity and quality of hay. Total losses during rain-free drying and drying interrupted by rain have been reported by many workers (Cameron, 1966; Kormos and Chestnutt, 1968a; Medling, 1964), but the information is of limited value for simulation purpose because a separate estimation of losses due to respiration and rainfall is essential to update the yield and digestibility under various weather conditions. In the following sections a detailed review of literature of only those studies that allow us to estimate these losses separately is presented.

There is evidence (Cameron, 1966; Kormos and Chestnutt, 1968a; Honig, 1980) that under some weather conditions, there may be an increase rather than decrease in dry matter due to continued photosynthesis after cutting. However, it is unlikely that the photosynthesis will continue beyond the first few hours of drying (Nash, 1978). Also, there is no study which correlates this increase in dry matter with weather. Hence, any gain in dry matter has been neglected in this study.

7.3.1 Losses due to respiration

When a crop is cut the plant cells remain alive and continue to respire. This process uses carbohydrates which are highly digestible. Wood and Parker (1971) represented the respiration equation as:
180g \( \text{C}_6 \text{H}_{12} \text{O}_6 \) + 192g \( \text{O}_2 \) \( \rightarrow \) 264g \( \text{CO}_2 \) + 108g \( \text{H}_2\text{O} \) + 677 KCal \hfill (7.4)

According to above equation, every gram of \( \text{CO}_2 \) produced represents a loss of 0.682 gram of carbohydrate from dry matter of plants. Respiration rate usually is determined by drawing a \( \text{CO}_2 \) free stream of air past the plant material and measuring any \( \text{CO}_2 \) produced in a fixed time period.

During field-drying, respiration rate is influenced mainly by the moisture content of the crop and air temperature. Respiration rate declines as the moisture content decreases and it ceases at a moisture content of about 30% on a dry basis (Greennill, 1959b); conversely, the respiration rate increases with an increase in temperature.

Wood and Parker (1971) developed the following equations expressing the effect of moisture content and temperature on the respiration rate.

\[
RR = 0.177 \, e^{0.069t \, (0.056 \, m - 1.53)} \quad \text{for } 5^\circ \text{C} < t < 25^\circ \text{C}, \, m > 27.3\%
\]

\[
RR = 0.056 \, m - 1.53 \quad \text{for } 25^\circ \text{C} < t < 45^\circ \text{C}, \, m > 27.3\%
\]

where \( RR \) = respiration rate, mg \( \text{CO}_2 \)/g DM per h

\( m \) = moisture content, % wet basis

\( t \) = air temperature, \(^\circ \text{C}\)
Equation 7.6 is more suitable for a barn hay drying process as it covers the temperature range of 25 - 45°C. For a field-drying process, Equation 7.5 can be used, as it covers the temperature range of 5 - 25°C which normally is encountered in the field. However, this equation was developed by combining data published by Greenhill (1959b), Wilkinson and Hall (1966) and Zimmer (1967).

Recently, Honig (1980) performed experiments with grass and presented his results in the form of graphs showing the effect of dry matter (DM) content and temperature on the respiration loss. In preference to Equation 7.5 developed by Wood and Parker, the results of Honig were used in this thesis to develop an expression for respiration as his data were from a single set of experiments and covered the temperature range from 5 - 30°C. Honig's original graph and data are given in Appendix G. From these, the following expression was developed.

\[
RL = 1.17 \times 10^{-6} \ M \ e^{0.066t} \tag{7.7}
\]

\[R^2 = 0.98, \ SE = 0.0011, \ N = 42\]

where \( RL \) = fractional dry matter loss per hour due to respiration

\( M \) = moisture content, % dry basis

\( t \) = air temperature, °C

\( R^2 \) = multiple coefficient of determination

\( SE \) = standard error of estimate

\( N \) = number of observations
The respiration losses based on Equation 7.7 are illustrated graphically in Figure 7.1. Conditioning of crop may slightly stimulate the respiration of cut crop (Simpson, 1961) but no quantitative data were available to develop an expression similar to Equation 7.7. Hence, the same equation was used to determine the respiration losses for conditioned hay.

As a result of solar radiation, air temperature in the vicinity of the swath is usually 1 - 6°C above the ambient temperature (Jones and Harris, 1980). Thus, in the simulation model the temperature of swath was taken as 3°C higher than the ambient temperature during the daytime.

The dry matter loss due to respiration in bales was also determined using Equation 7.7 but the temperature of the bales was assumed to be 5°C higher than the ambient temperature as suggested by Parke et al. (1978).

7.3.2 Losses due to rainfall

Rainfall during field-drying results in rewetting of partially dried crop which can lead to a serious loss of yield and digestibility of hay. Loss due to rainfall can be classified as:

(i) direct loss, and
(ii) indirect loss.

Direct loss is the loss of soluble material, mainly sugars, due to leaching. Indirect loss occurs because of:

(i) prolonged respiration of wet crop, and
Figure 7.1 Effect of moisture content on respiration loss at different temperatures (from Honig, 1980).
(ii) additional physical loss of plant material during raking of wet crop to enhance drying and subsequent baling.

A freshly cut crop is more resistant to leaching by rain than a partially dried one mainly because the plant cells remain turgid for a few hours after cutting (Nash, 1978). Hence, leaching loss during the field-drying process is mainly a function of moisture content of crop and the amount of rain. There have been very few studies that have investigated the effect of rainfall on leaching loss.

Fleischmann (1912) conducted laboratory experiments by applying 9.14 mm of artificial rain to fresh and partially dried grass samples. Rain application time was spread over a period of 24 hours; 75% of rain was applied during the first 9 hours of the day at an interval of half to three quarters of an hour and the remaining 25% rain was applied during the rest of the period. Dry matter loss due to leaching was low (0.2%) for fresh grass samples and losses of 1.1, 1.4 and 1.9% were found for grass samples which were partially dried for 3, 5 and 7 days, respectively. No mention was made of moisture contents of samples before the application of rain.

A study carried out by Gordon et al. (1966) showed an increase in dry matter loss of 1.4% for each 10 mm of rainfall when lucerne samples at 32% moisture content (wet basis) were rewetted by varying amounts of artificial rain. This loss included the leaching as well as the respiration loss because the samples were redried for one day before determining the dry matter loss.
Conditioning treatment by damaging the plant cells makes the crop more sensitive to leaching. Kormos and Chestnutt (1968b) carried out experimental work on rye grass/clover mixtures to investigate the effect of rain on dry matter loss of conditioned hay. Contrary to the results of Fleischmann (1912), they found that leaching loss for conditioned hay was higher for the freshly cut crop than a drier crop. Dry matter losses due to leaching were 1.7, 0.8 and 0.6% when 6 mm of simulated rain was applied immediately, 40 hours and 90 hours after cutting, respectively. No other study was found to support their rather unusual results. The moisture contents of grass samples were not mentioned and the effect of different amounts of rainfall on leaching loss also was not investigated.

Dernedde and Wilmschen (1969) performed experiments by applying 10 mm of artificial rain on unconditioned and conditioned grass samples. Rain application time was an hour only and moisture content of samples was 20% (wet basis). Leaching loss of conditioned grass was higher (2%) than the unconditioned grass (1%). Again, the effect of different amounts of rainfall and moisture contents was not investigated.

Moller and Skovborg (1971) conducted laboratory trials by applying 20 mm of artificial rain on grass-clover mixtures at different dry matter contents. Their results which are given in Table 7.2 show that leaching loss increases as the moisture content (MC) of material decreases, for both the unconditioned and conditioned samples. The loss for conditioned hay was more than the unconditioned hay at the same moisture content.
Table 7.2  Leaching losses due to rainfall (from Moller and Skovborg, 1971)

<table>
<thead>
<tr>
<th>DM Content (%)</th>
<th>Equivalent MC (%)</th>
<th>Leaching loss (% mm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mown material</td>
</tr>
<tr>
<td>20</td>
<td>400.0</td>
<td>0.04</td>
</tr>
<tr>
<td>30</td>
<td>233.3</td>
<td>0.12</td>
</tr>
<tr>
<td>52</td>
<td>92.3</td>
<td>0.34</td>
</tr>
<tr>
<td>74</td>
<td>35.4</td>
<td>0.41</td>
</tr>
</tbody>
</table>

In the absence of any systematic study relating the leaching loss to different moisture contents and various amounts of rainfall, the results of Moller and Skovborg were used to develop separate equations for unconditioned and conditioned hay. This was possible because the moisture contents at the time of application of rain were available. Mown and flailed material was considered equivalent to conditioned hay, notwithstanding the fact that flailed material would represent a relatively severe treatment compared to the conditioning treatment by a crusher or crimper. The equations are given below and graphically represented in Figure 7.2. It should be noted that the equations are based on only 4 items of data and may be subject to very large sampling errors.

\[
LL = 0.00563 e^{-0.0066M}, \text{ for unconditioned hay} \quad (7.8)
\]

\[
LL = 0.00598 e^{-0.0049M}, \text{ for conditioned hay} \quad (7.9)
\]

where \( LL = \text{fractional dry matter loss (per mm of rainfall) due to leaching} \)

\( M = \text{moisture content at the start of rain, % dry basis} \)
Figure 7.2 Effect of moisture content on leaching loss due to rainfall (from Møller and Skovborg, 1971).
The impact of raindrops may result in leaf loss due to shattering but its effect is not included in the model because no quantitative data were available for pasture hay.

7.4 Dry Matter Losses During Raking

After drying the crop to a suitable moisture content, the raking operation is carried out to gather the partially dried crop from swaths into windrows for further drying and finally for baling. Losses during raking occur due to shattering of plant material, mainly leaves, and the inability of the rake to gather 100% of crop lying in the swath.

Losses of from 1.5 to 25% have been reported (Friesen, 1977; Savoie, 1982; Anderson, 1981) depending upon the type of crop and condition of crop at the time of raking. However, no extensive research has been carried out to relate the factors such as moisture content and crop maturity to raking losses. Based on the review of literature by Driessen and Kand (1973), Parke and Dumont (1979) developed a curve relating mechanical losses to moisture content. It is redrawn here as Figure 7.3 after changing moisture content from wet to dry basis. Based on this curve, the following relationship was developed for use in the simulation model.

\[ RKL = 0.267 M^{-0.745} \]  

(7.10)

where

- \( RKL \) = fractional dry matter loss due to raking
- \( M \) = moisture content of crop at the time of raking, \( \% \)
- dry basis.
Figure 7.3 Effect of moisture content on dry matter loss during raking operation (from Parke and Dumont, 1979).
7.5 Dry Matter Losses During Baling

Hay is usually baled at a moisture content of about 25% (dry basis). In this condition leaves become very fragile and are subject to considerable loss during the baling operation. Baling losses are comprised of:

(i) pickup loss, and
(ii) bale chamber loss.

Balers with bale-ejectors also result in bale-ejector loss.

The detailed description of these losses is given by Whitney (1966) who found that dry matter losses from a rectangular baler ranged from 1.4 to 3.8% of yield. He also estimated a further loss of 0.3 to 1.0% for a baler with bale ejector. However, Friesen (1977) measured loss of 2.5 to 4.0% for a rectangular baler but no additional loss when baler was fitted with a bale ejector. PAMI (1979) reported that the total loss from rectangular balers in most conditions will be less than 4%.

Dry matter losses for large round balers may be higher than rectangular balers. PAMI (1977) found that losses for round balers could vary between 5 and 27% depending upon the moisture content and yield of crop. In light crops the losses are higher than in heavy because to make one large round bale the machine has to travel further which results in more agitation of crop material while the bale is being formed. Friesen (1977) measured round baler losses up to 15% whereas Anderson et al. (1981) and Nehrir et al. (1978) noted an average loss of 10%.

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No quantitative data have been found which relates the baling loss with moisture content and crop yield. Shepherd (1959) presented a graph between moisture content and dry matter loss based on a laboratory test. However his results could not be used because the range of moisture content considered was 8 - 18% which is well below the normal moisture range encountered in practice. In a subsequent paper Shepherd (1960) presented his results, again on the basis of the laboratory test, showing the effect of different combinations of leaf and stem moisture contents on the dry matter loss. These results also could not be used for two reasons. Firstly, the pasture growth model (Chapter 4) does not predict the separate yield of leaves and stems. Secondly, the swath hay drying model (Chapter 5) does not estimate the moisture content of leaves and stems separately, but rather predicts an average moisture content of all the material.

In addition to the moisture content of crop, other factors such as yield, maturity and speed of operation are likely to affect the dry matter losses during baling. The effect of speed may be significant as the physical impact on the dried crop is more at higher speeds which could result in higher losses. Further, balers are likely to be operated faster at lower yields and thus losses could be higher under these conditions. Crop maturity also may affect the losses due to variations in leaf to stem ratio. Clearly, more research is necessary to make a better estimate of mechanical losses. Because of the limitations of suitable data, baling losses in the present simulation model are determined using the Equation 7.10 presented in the previous section, notwithstanding the fact that baling loss could be different to
raking loss at the same moisture content.

7.6 Changes in Digestibility

Qualitative losses occur at every stage of hay-making due either to a change in chemical composition of the plant or to a change in leaf to stem ratio of the material. For this study, qualitative losses are represented by the change in digestibility. In the following sections, methods are described which estimate the digestibility loss due to mechanical operations and environmental factors.

7.6.1 Mechanical operations

Mechanical operations such as cutting, raking and baling do not alter the chemical composition of plants, but the material lost during these operations is mainly leaves so that the leaf to stem ratio of hay is altered. This results in a decrease in digestibility of the hay since the leaves are highly digestible. The separate estimation of loss of leaf and stem could not be made due to lack of data. However, it was assumed that the digestibility of material lost was about 20% higher than the remaining material (Simmons, 1985). The fractional digestibility loss was then calculated for each mechanical operation using Equation 7.11, the derivation of which is given in Appendix H.

\[
b_m = \frac{0.2 \ a_m}{1 - a_m} \quad (7.11)
\]
where \( b_m \) = fractional loss of digestibility due to the mechanical operation
\( a_m \) = fractional loss of dry matter due to the mechanical operation

7.6.2 Environmental factors

During field-drying, the environmental factors, viz. temperature and rainfall result in respiration and leaching respectively. These cause losses which consist of 100% digestible nutrients so that they result in an overall decrease of digestibility. Equation 7.12 below is used to evaluate the fractional loss in digestibility due to respiration and that due to leaching.

\[
b_e = \frac{D_b - (D_b - a_e)/(1 - a_e)}{D_b}
\]  

(7.12)

where \( b_e \) = fractional loss of digestibility due to respiration or leaching as appropriate
\( D_b \) = digestibility of hay before it is affected by respiration/leaching
\( a_e \) = fractional loss of dry matter due to respiration/leaching

The derivation of Equation 7.12 is given in Appendix I.

7.7 Summary

Based on the available literature, losses during hay-making are estimated. Tables 7.3 and 7.4 summarize loss values which are
### Table 7.3  Dry matter losses during hay-making.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Fractional dry matter loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Cutting</td>
<td></td>
</tr>
<tr>
<td>(i) mower</td>
<td>0.01</td>
</tr>
<tr>
<td>(ii) mower-conditioner</td>
<td>0.02</td>
</tr>
<tr>
<td>2. Drying</td>
<td></td>
</tr>
<tr>
<td>(i) Respiration</td>
<td>Equation 7.7</td>
</tr>
<tr>
<td>(ii) Rainfall</td>
<td></td>
</tr>
<tr>
<td>(a) leaching (unconditioned)</td>
<td>Equation 7.8</td>
</tr>
<tr>
<td>(b) leaching (conditioned)</td>
<td>Equation 7.9</td>
</tr>
<tr>
<td>(c) additional respiration</td>
<td>Equation 7.7</td>
</tr>
<tr>
<td>(d) additional raking loss</td>
<td>Equation 7.10</td>
</tr>
<tr>
<td>3. Raking</td>
<td>Equation 7.10</td>
</tr>
<tr>
<td>4. Baling</td>
<td>Equation 7.10</td>
</tr>
</tbody>
</table>

### Table 7.4  Change in digestibility during hay-making.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Fractional digestibility loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Mechanical operations</td>
<td></td>
</tr>
<tr>
<td>(i) Cutting</td>
<td>Equation 7.11</td>
</tr>
<tr>
<td>(ii) Raking</td>
<td>Equation 7.11</td>
</tr>
<tr>
<td>(iii) Baling</td>
<td>Equation 7.11</td>
</tr>
<tr>
<td>2. Environmental factors</td>
<td></td>
</tr>
<tr>
<td>(i) Respiration</td>
<td>Equation 7.12</td>
</tr>
<tr>
<td>(ii) Leaching</td>
<td>Equation 7.12</td>
</tr>
</tbody>
</table>
used in the simulation model. The review of literature suggests that, in future experimental research, the emphasis should be given to refining these estimates of losses. Separate determination of loss of leaves and stems due to mechanical operations is desirable from the standpoint of accurate estimation of loss in quality. The effects of moisture content, speed of operation and yield on these losses also should be investigated. Leaching loss data are scanty and research in this field would help to determine the extent of loss due to rain.
CHAPTER 8

WEATHER FORECAST MODEL

Hay-making in southern Australia is carried out in a variable and somewhat unpredictable weather regime. Weather has a significant influence on the field-drying process which takes 2-3 days in this region, so that any attempt to improve the management of hay-making will involve the use of the only objective weather information available, i.e. the three-day forecast.

A number of hay-making simulation models (Section 2.2) have been reported in the literature. Most of these studies have used historical weather data, but only that of Parke et al. (1978) has included forecasts. In that study three-day forecasts were made from the historical weather data which consisted of a single digit from 1 (three rain-free days) to 5 (three rainy days) based on the occurrence of rain. A random variate was introduced which increased or decreased the forecast number. The actual probabilities of predicting different types of three-day forecasts were not considered.

Dyer and Baier (1981) developed a procedure for estimating the probability of field-drying hay in four days or less when the first one or more days after cutting were known to have no rain. They did not use reliability of forecasts and different types of forecasts were not considered.
This chapter describes a method for preparing three-day forecasts for known weather data and making assessments for the purpose of scheduling hay-making operations.

8.1 Role of Weather Forecasts in Hay-making Simulation

Historical weather data often are used to analyse hay-making systems; however, weather forecasts covering a large number of years normally are not available and, even if they are, they cannot be used because of the improvements in forecasting which have occurred with the passage of time. Although the actual weather for a historical three-day period is now known, it must be remembered that the simulation addresses the past point in time, just prior to the three-day period in question, at which neither the farmer nor the Bureau of Meteorology know the weather to come. A pre-requisite for simulating the decision-making process of a farmer is to represent the generation of a three-day forecast for a known future weather pattern. This can be done by using the historical weather data combined with the known reliability of three-day forecasts, expressed in terms of probabilities of making different forecasts, given that a particular weather pattern is to occur.

The next step is to simulate the farmer's decision-making process itself. The farmer normally has a perception of weather pattern through his experience and, after listening to the forecast, he makes his own judgement of the weather based on the confidence he has in that forecast. This decision-making process can be simulated in two stages:
(i) historical probabilities of occurrence of different types of three-day weather during the hay-making season can be used to simulate the farmer's perception of weather pattern, and

(ii) Bayes' theorem (De Neufville and Stafford, 1971) can be used to revise these historical probabilities and thus simulate his use of new information, i.e., the weather forecast, to decide whether or not to cut. The decision process itself is represented by assuming that the farmer will decide to cut if the revised probability of three dry days exceeds a specified value.

8.2 Collection of Weather Forecast Data

The weather for three days can be divided into eight different types (Table 8.1) based only on the occurrence or non-occurrence of rain during three consecutive days, i.e., today (Day-1), tomorrow (Day-2) and the next day (Day-3).

<table>
<thead>
<tr>
<th>Weather Number</th>
<th>Day-1</th>
<th>Day-2</th>
<th>Day-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>D</td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>2</td>
<td>D</td>
<td>D</td>
<td>R</td>
</tr>
<tr>
<td>3</td>
<td>D</td>
<td>R</td>
<td>D</td>
</tr>
<tr>
<td>4</td>
<td>D</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>5</td>
<td>R</td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>6</td>
<td>R</td>
<td>D</td>
<td>R</td>
</tr>
<tr>
<td>7</td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>8</td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
</tbody>
</table>
The three-day forecasts for five years (1980-1984) covering the period from October-December were obtained from the Bureau of Meteorology, Melbourne. Each day's forecast was classified into "D" (dry day) when no rain was predicted and "R" (rainy day) when rain was predicted. Actual rainfall data for the same period were also obtained. The data are given in Appendix J.

8.3 Analysis of Weather Forecast Data

A computer program was written to analyse this weather forecast data. The three-day forecasts were first divided into a predicted forecast number according to the classification given in Table 8.1. Actual rainfall data were used to determine actual weather type for the three-day period commencing on each date and these also were given a number. Actual weather and three-day forecasts were then compared to investigate the reliability of forecasts. The reliability of forecasts can be checked in two ways:

(i) probability of making different types of forecasts for known weather of three days, and
(ii) probability of experiencing different types of three-day weather for a given forecast.

The results are presented in Tables 8.2 and 8.3. It may be noted that three dry days were predicted on only 34% of those occasions on which three dry days actually occurred. In contrast, three dry days actually occurred on 67% of those occasions for which three dry days were predicted.
Table 8.2 Probabilities of making different types of forecasts for a known weather of three days.

<table>
<thead>
<tr>
<th>Actual weather type</th>
<th>Probability of forecasting weather number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>.343</td>
</tr>
<tr>
<td>2</td>
<td>.211</td>
</tr>
<tr>
<td>3</td>
<td>.188</td>
</tr>
<tr>
<td>4</td>
<td>.103</td>
</tr>
<tr>
<td>5</td>
<td>.109</td>
</tr>
<tr>
<td>6</td>
<td>.000</td>
</tr>
<tr>
<td>7</td>
<td>.026</td>
</tr>
<tr>
<td>8</td>
<td>.000</td>
</tr>
</tbody>
</table>

Table 8.3 Probabilities of experiencing different types of three-day weather for a given forecast.

<table>
<thead>
<tr>
<th>Forecast Number</th>
<th>Probability of experiencing actual weather of type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>.670</td>
</tr>
<tr>
<td>2</td>
<td>.600</td>
</tr>
<tr>
<td>3</td>
<td>.406</td>
</tr>
<tr>
<td>4</td>
<td>.241</td>
</tr>
<tr>
<td>5</td>
<td>.421</td>
</tr>
<tr>
<td>6</td>
<td>.400</td>
</tr>
<tr>
<td>7</td>
<td>.186</td>
</tr>
<tr>
<td>8</td>
<td>.078</td>
</tr>
</tbody>
</table>
8.4 Assessment of Weather Forecasts

Perfect weather forecasts would facilitate the identification of policies for hay-making. However, forecasts are not accurate and improvements in forecasting are likely to occur at a slow rate. Therefore, increased benefits from forecasts can be obtained only by an increase in our skill in using them. Hence, a method was developed to revise the probability of experiencing different types of three-day weather, given that a particular forecast has been made.

8.4.1 Historical probabilities of three-day weather

Daily rainfall data (1941-1983) for Laverton Station were obtained from the Bureau of Meteorology, Melbourne. These were used to determine the historical probabilities of the occurrence of different types of three-day weather during the hay-making season (1 October - 31 December). The procedure used was as follows.

Each day of the season was classified either as a dry day (if there was no rain) or a rainy day (if there was rain). Three-day weather for each date was then given a number varying from 1 to 8 depending upon the weather pattern. In order to determine the probabilities of different types of three-day weather commencing on a given date, the data for three days preceding that date and three days after the date also were considered. Thus, the total number of observations for each date was 301 [43 (years) × 7 (days)]. For each date, the number of cases under each type of
three-day weather (as defined in Table 8.1) was determined. The probabilities for each type of weather were then calculated as the number of cases in a given type to the total number of observations.

The probability values are given in Appendix K. For the purpose of smoothing the data, linear equations of the following type were developed using a regression analysis subprogram available in SPSSx package (Noursis, 1983).

\[ P_n = a + b \times \text{DAY} \quad (8.1) \]

where \( P_n \) = probability of occurrence of \( n^{th} \) type of weather

\( \text{DAY} \) = number of days after 30 September

\( a \) = constant

\( b \) = regression co-efficient for \( \text{DAY} \)

The actual data and the regression lines are shown in Figure 8.1 while the regression equations are given in Table 8.4. It may be noted from this figure that the probability of occurrence of three dry days increases as the season progresses. Conversely, the probability of occurrence of three wet days is greater during the early part of the season.
Figure 8.1: Historical probabilities of occurrence of different types of three-day weather during the haymaking season.
### Table 8.4 Regression equations for determining historical probabilities of occurrence of different types of three-day weather.

<table>
<thead>
<tr>
<th>Weather type</th>
<th>Constant (a)</th>
<th>Regression coefficient for DAY (b)</th>
<th>Equation number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.177</td>
<td>2.97 x 10^{-3}</td>
<td>8.2</td>
</tr>
<tr>
<td>2</td>
<td>0.120</td>
<td>0.00</td>
<td>8.3</td>
</tr>
<tr>
<td>3</td>
<td>0.061</td>
<td>2.03 x 10^{-4}</td>
<td>8.4</td>
</tr>
<tr>
<td>4</td>
<td>0.130</td>
<td>-6.28 x 10^{-4}</td>
<td>8.5</td>
</tr>
<tr>
<td>5</td>
<td>0.122</td>
<td>0.00</td>
<td>8.6</td>
</tr>
<tr>
<td>6</td>
<td>0.071</td>
<td>-4.28 x 10^{-4}</td>
<td>8.7</td>
</tr>
<tr>
<td>7</td>
<td>0.132</td>
<td>-6.26 x 10^{-4}</td>
<td>8.8</td>
</tr>
<tr>
<td>8</td>
<td>0.188</td>
<td>-1.51 x 10^{-3}</td>
<td>8.9</td>
</tr>
</tbody>
</table>

### 8.4.2 Revised probabilities of three-day weather

Historical probabilities of occurrence of different types of three-day weather can be revised using Equation 8.10 which is based on Bayes' theorem.

\[
     \frac{R_{j,k}}{R} = \frac{HP_j \times PF_{k,l}}{3 \sum_{i=1}^{8} HP_i \times PF_{k,l}} \quad (8.10)
\]

Where \( R_{j,k} \) = revised probability of experiencing \( j \)th type of three-day weather for a given day during the season given that the \( k \)th type of weather has been predicted.

\( HP_j \) = historical probability of occurrence of \( j \)th type of three-day weather for a given day during the season.
\[ \text{PF}_{k,j} = \text{probability of the } k^{\text{th}} \text{ type of weather being predicted when the } j^{\text{th}} \text{ type of weather will actually occur.} \]

An application of Equation 8.10 can be demonstrated. Let us assume that we want to estimate the probability of experiencing three dry days from 1 October, 1 November and 1 December for different types of forecasts. Using Equations 8.2 to 8.9, the historical probabilities of occurrence of different types of weather can be determined as given in Table 8.5. By using the reliability of forecasts (Table 8.2) and these historical probabilities, Equation 8.10 can be used to revise the estimate of probabilities of experiencing three dry days (Table 8.6).

It may be seen from Table 8.6 that the revised probability of the occurrence of three dry days increases for all types of forecasts as the season progresses, simply because, as the historical data shows, dry weather is more likely in the later part of the season. What is more revealing is that the farmer could have an estimate of probability of three dry days for a given type of forecast and, depending upon the risk he is prepared to take, he can choose to cut the crop even on those days when the forecast for three days is not necessarily D, D, D. The use of revised probabilities in scheduling hay-making operations is demonstrated in Chapter 10 where the simulation experiments are described.
### Table 8.5 Historical probabilities of occurrence of different types of three-day weather.

<table>
<thead>
<tr>
<th>Weather type</th>
<th>Historical probability of given weather type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 October</td>
</tr>
<tr>
<td>1</td>
<td>0.180</td>
</tr>
<tr>
<td>2</td>
<td>0.120</td>
</tr>
<tr>
<td>3</td>
<td>0.061</td>
</tr>
<tr>
<td>4</td>
<td>0.129</td>
</tr>
<tr>
<td>5</td>
<td>0.122</td>
</tr>
<tr>
<td>6</td>
<td>0.071</td>
</tr>
<tr>
<td>7</td>
<td>0.131</td>
</tr>
<tr>
<td>8</td>
<td>0.186</td>
</tr>
</tbody>
</table>

### Table 8.6 Revised probabilities of experiencing three dry days for different types of weather forecasts.

<table>
<thead>
<tr>
<th>Forecast type</th>
<th>Revised probability of three dry days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 October</td>
</tr>
<tr>
<td>1</td>
<td>0.480</td>
</tr>
<tr>
<td>2</td>
<td>0.397</td>
</tr>
<tr>
<td>3</td>
<td>0.200</td>
</tr>
<tr>
<td>4</td>
<td>0.107</td>
</tr>
<tr>
<td>5</td>
<td>0.213</td>
</tr>
<tr>
<td>6</td>
<td>0.203</td>
</tr>
<tr>
<td>7</td>
<td>0.075</td>
</tr>
<tr>
<td>8</td>
<td>0.026</td>
</tr>
</tbody>
</table>
The cumulative probabilities of making different types of weather forecasts for known weather were determined (Table 8.7) using the results presented in Table 8.2. A computer program (FORECAST) was written in FORTRAN-77 to develop three-day forecasts from known weather data and then revise the probability of experiencing different types of three-day weather. A flow chart of the program is shown in Figure 8.2. The program first identifies the actual weather type for three days using the historical rainfall data. The standard Monte Carlo Method (Gordon 1978) is then used to generate the weather forecast by application of a selected random fraction to the appropriate row of cumulative probabilities in Table 8.7. Historical probabilities of occurrence of different types of three-day weather are then revised by following the procedure outlined in Section 8.4.

<table>
<thead>
<tr>
<th>Actual weather type</th>
<th>Cumulative probability of forecasting weather number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>.343</td>
</tr>
<tr>
<td>2</td>
<td>.211</td>
</tr>
<tr>
<td>3</td>
<td>.188</td>
</tr>
<tr>
<td>4</td>
<td>.103</td>
</tr>
<tr>
<td>5</td>
<td>.109</td>
</tr>
<tr>
<td>6</td>
<td>.000</td>
</tr>
<tr>
<td>7</td>
<td>.026</td>
</tr>
<tr>
<td>8</td>
<td>.000</td>
</tr>
</tbody>
</table>
Figure 8.2 Flow chart of a subroutine (FORECAST) to make and analyse three-day weather forecasts.
8.6 Summary

Three-day weather forecast data for five hay-making seasons were analysed with a view to developing a procedure of making forecasts for known historical weather information. In this way it was possible to make forecasts according to the present state of knowledge. Bayes' theorem was applied to revise the estimates of probability of experiencing different types of three-day weather based on historical information and current weather forecast. These revised estimates of probability of three-day weather will be used to schedule hay-making operations.
CHAPTER 9

MANAGEMENT MODEL

This chapter describes a management model which is used in the hay-making simulation to achieve the following objectives:

(i) to determine which operations are feasible at the decision time,

(ii) to set the priority of operations, and

(iii) to prepare an actual schedule of operations depending on their feasibility and priority.

In the field situation there is theoretically an infinite flexibility with which management decisions can be made and changed, but practical limitations reduce this considerably. In seeking to simulate this real management process a decision therefore has to be made with regard to the time increment for decision making. Too long an interval will lead to inflexibility while too short an interval will lead to excessive computing time.

The choice of a scheduling time interval of one hour was felt to be more realistic and practical than a half or full day which would have allowed only two starting times for field operations. For example, hay may be ready for baling after a few hours of drying in the morning or afternoon. Under these conditions scheduling of operations will be more realistic if an increment of one hour is used. While the hay-making process is simulated
on an hourly basis, the decision to prepare a schedule of operations can be made at any interval from one to several hours.

9.1 Feasibility of Operations

Four machinery operations, namely, cutting, raking, baling and carting are simulated. A simplified flow chart of the management model is shown in Figure 9.1. The following sections describe the procedure which was used to ascertain the feasibility of each of these operations.

9.1.1 Cutting

Cutting all the crop at the first opportunity is unlikely to produce the best quality hay. In practice, there is no widely accepted single procedure which can be used to decide whether to "cut" or "not cut" the crop at any given time during the season. However, weather prospects for 2-3 days after cutting and the amount of cut crop already lying in the swath are important factors which a farmer must take into consideration in making his decision.

Weather prospects after cutting are represented by the perceived probability of experiencing three dry days. This is determined using the weather forecast for three days, the reliability of forecasts and the historical probabilities of the occurrence of different types of three-day weather as described in Chapter 8.
Figure 9.1 Simplified flow diagram of management model.
The amount of cut crop lying in the swath is expressed in terms of the number of days of harvest capacity of the system. For example, one day harvest capacity of the system is taken as equal to the amount of hay which can be baled in a day. An average baler-day is taken as equal to six actual working hours (Vasey and Simmons, 1957).

The above two criteria are incorporated in the model such that for cutting to proceed:

(i) the revised probability of experiencing three dry days should be greater than a specified value, and
(ii) the hay lying in the swath should be less than a specified number of days of harvest capacity of the system.

Further, on any given day cutting is allowed to occur as long as the crop cut on that day does not exceed the amount which can be harvested in one day by a given machinery system.

Both of the above factors represent the risk a farmer is prepared to take at the time of cutting. The values of these parameters are given as input and their effects on the system performance can be investigated by the model.

9.1.2 Raking

The raking operation normally is carried out towards the end of drying to bring two or more swaths together to form a windrow in preparation of the hay for the baling operation. However, some farmers perform this operation earlier in the drying cycle and
allow the crop to dry further in windrows. The preference between the two alternatives is usually influenced by personal choice and the practice varies from one district to another (Simmons, 1985). Thus, a provision is made in the model to allow for raking the partially dried crop at different moisture contents.

The feasibility of the raking operation is ascertained by comparing the moisture content of each plot lying in the field with a specified raking moisture content. If a plot of hay is found to be ready for raking, then the plots within 10% of the specified moisture content limit also are considered suitable for raking. This is necessary to simulate actual practice because a farmer normally will not stop the operation after raking one plot considering that the next plot is not exactly at the same desired moisture content. Moreover, it is difficult to distinguish within 10% (dry basis) the moisture of a highly variable material such as hay in the field.

Sometimes hay in windrows may get wet due to rain, especially if the raking operation is carried out early in the drying cycle. Turning of wet windrows may then be necessary in order to dry the lower layers of crop. In practice, the need to turn the windrows may depend upon factors such as the amount of rainfall, rainfall intensity, the moisture content of the hay at the time of rainfall and the density of windrow. No quantitative data were found to decide on these factors. Therefore, in the present model, the only variable considered is rain. If rain of more than 5 mm falls on raked hay, its state is then changed to
unraked and it is re-raked again at a suitable moisture content.

9.1.3 Baling

The baling operation usually is carried out at a stage when the average moisture content of the hay is around 25% (dry basis). One of the objectives of the present study was to investigate the effect of baling at a higher than normal moisture content and treating hay with preservatives for safe storage. Thus, the present model allows baling of the hay at different moisture contents.

In order to determine whether any raked hay is ready for baling, the moisture content of each raked plot lying in the field is compared to the specified baling moisture content. Again, for the reasons explained in Section 9.1.2, if a plot of hay is found to be suitable for baling, then the plots within 5% of specified moisture content are also considered to be ready for this operation.

9.1.4 Carting

Hay may be carted immediately after the baling operation. However, sometimes hay may not be moved to the store immediately due to the limitations of labour and machinery. Such hay may get wet from rain. Wet bales are carted to the store only after the rain water is evaporated and the moisture content has dropped sufficiently. The moisture content of hay bales is updated using the baled hay drying model described in Chapter 6.
9.2 Priority of Operations

Once it is found which operations are possible at a decision time, an order of priority is necessary if the feasible operations are such that they cannot be carried out simultaneously because of limitation of labour and/or machinery. In practice, no widely accepted method exists which can be used to ascertain the priority of hay-making operations. In the model, an arbitrary though logical method is used to establish such a priority. The order is given as follows:

<table>
<thead>
<tr>
<th>Operation</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baling</td>
<td>1</td>
</tr>
<tr>
<td>Raking</td>
<td>2</td>
</tr>
<tr>
<td>Cutting</td>
<td>3 or 4</td>
</tr>
<tr>
<td>Carting</td>
<td>3 or 4</td>
</tr>
</tbody>
</table>

Baling is always given a first priority because damage to hay at lower moisture contents is serious if it gets wet by rain. The second priority is given to raking because it enhances the drying rate of hay and thus reduces the risk of adverse weather. If cutting is in the plan and carting also is feasible, then the relative importance of each is decided depending upon the possibility of rain on the current day. If the revised probability of the current day being dry is higher than the revised probability of the current day being rainy, then cutting is given higher priority than carting and vice versa.
9.3 Schedule of Operations

Based on the feasibility and priority of operations, the actual schedule of operations is prepared. For this purpose, labour and machinery are first allocated to an operation with the highest priority and then to the operations with lower priorities.

While allocating labour and machinery to the feasible operations, care is taken to make an optimum use of labour. For example, assume that there are two men on a farm and that the following operations are feasible with a priority as listed.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Priority</th>
<th>Labour required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baling</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Carting</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Cutting</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

After allocating labour to the baling operation, only one man is left and the operation with next priority is carting for which the remaining labour is not sufficient. In this case, an operation with the next priority, i.e., cutting is considered in the schedule. This probably means that carting is postponed - a result which seems to be in accord with farmers' practice.
This chapter describes the results of simulation runs based on 16 years (1968-1983) of historical weather data from Laverton, Victoria. The simulation model was used to determine how various hay-making policies might affect the performance of the system. The effects of conditioning the crop at the time of cutting, baling at a higher moisture content and treating hay with preservatives, perfect weather forecasts, system capacity and manpower also were investigated. The following two criteria were used for the purpose of comparing the performance:

(i) digestible dry matter (DDM) yield of hay, and
(ii) harvesting time expressed as number of days from the starting date of hay-making to the finishing date.

10.1 Input Data

10.1.1 General data

The following three major parameters were varied during the simulation runs:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>20 - 120 ha</td>
</tr>
<tr>
<td>Manpower</td>
<td>2 - 4</td>
</tr>
<tr>
<td>System size</td>
<td>small, medium and large</td>
</tr>
</tbody>
</table>
There were four operations, viz. cutting, raking, baling and carting. The number of men required and the moisture content (MC) limits for each operation are given in Table 10.1, while the description of the above three systems is given in Table 10.2. The net working rates of various operations were selected to cover the range of machinery sizes available in the market.

Table 10.1 Manpower requirements and moisture content limits for hay-making operations.

<table>
<thead>
<tr>
<th>Operation</th>
<th>No. of men</th>
<th>MC (%) dry basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Raking</td>
<td>1</td>
<td>60 (max.)</td>
</tr>
<tr>
<td>Baling</td>
<td>1</td>
<td>25 (max.)</td>
</tr>
<tr>
<td>Carting</td>
<td>2</td>
<td>25 (max.)</td>
</tr>
</tbody>
</table>

Table 10.2 Work rates of three hay-making systems.

<table>
<thead>
<tr>
<th>System</th>
<th>Net working rate of operation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cutting (ha h⁻¹)</td>
</tr>
<tr>
<td>Small</td>
<td>1.0</td>
</tr>
<tr>
<td>Medium</td>
<td>2.0</td>
</tr>
<tr>
<td>Large</td>
<td>3.0</td>
</tr>
</tbody>
</table>

The working time was from 09.00 to 13.00 h and again from 14.00 to 20.00 h with 13.00 to 14.00 h being a meal break. The overall season was assumed to be from 1 October to 31 December. The cutting operation was allowed as long as the digestibility of standing pasture was equal to or higher than 50%. Other operations were allowed up to end of the season.
10.1.2 Weather data

Weather data for the Laverton (Victoria) station were obtained from the Bureau of Meteorology, Melbourne. These data were:

(i) Three hourly data
   (a) dry bulb temperature
   (b) wet bulb temperature
   (c) rainfall

(ii) One hourly rainfall data

(iii) Half hourly radiation data

Since the simulation model uses one-hourly data, the above were transformed into this form as follows.

Dry and wet bulb temperatures were used to calculate vapour pressure deficit at the beginning and end of each three hour period; the vapour pressure deficits for intermediate hours were estimated by interpolation. The mean vapour pressure deficit for each hour was then determined by averaging the vapour pressure deficit values at the beginning and end of each hour.

There were some gaps in the one-hourly rainfall data and therefore it was not possible to use the data directly. Consequently, the three-hourly rainfall data were disaggregated into one-hourly data to fill these gaps. The procedure used is described in Appendix L.
Radiation data corresponded to the local mean time which was about half an hour less than the local standard time. Therefore, half an hour was added to the time for each observation before converting half hourly to hourly data.

The weather forecast model presented in Chapter 8 uses random numbers to prepare three-day forecasts. The sequence in which the random numbers are generated affects the weather forecasts which in turn influence the management decisions. Thus, each year's weather data was replicated five times, each time with a different sequence of random numbers.

10.2 Hay-making Policies

In hay-making, the operations other than cutting are carried out depending upon the suitability of cut crop in regard to its state and moisture content. However, there is no widely accepted single procedure which can be used to decide whether to cut more hay or not and, if so, how much to cut. The effects of the following factors were therefore investigated to establish an optimum policy for hay-making:

(i) **Weather prospects after cutting** represented by the revised probability of three dry days (day of cutting and the next two days); the method of its estimation is described in Chapter 8.

(ii) **Swath area limit** defined as the area cut but not yet baled. This was expressed in number of days of harvest (baling) capacity of the system.
(iii) **Maturity at the start of season.** In this context the "start of season" is considered to be the date on which the digestibility of the standing pasture first reaches the specified value at which cutting is allowed to start. As maturity is inversely related to digestibility, the latter is employed as the (inverse) measure of maturity.

For the purpose of evaluating various hay-making policies, a 50 ha crop, 2 men and medium system were considered. The results are explained in the following sections with the help of figures in which the "policy description" table is used to specify the values of the above factors. An asterisk, *, is used to indicate the factor whose value was varied.

In later sections (10.4 to 10.7), the effects of system capacity, manpower, crop area and required minimum hay quality also are described.

10.2.1 **Weather prospects after cutting**

The damage to a cut crop is highly dependent upon the weather during drying, therefore, the weather prospects after the proposed time of cutting become the first and the most important criterion for a decision on whether to "cut" or "not cut". Weather forecasts for 3 days can be used to schedule the cutting operation, but they are not always perfect. Hence, it was considered more appropriate to base the decision on a revised probability value of 3 dry days (Chapter 8).
The model was run for different probabilities and the results are shown in Figure 10.1. It can be seen from this figure that as the minimum acceptable revised probability of 3 dry days was increased from 0.2 to 0.5, the DDM yield of hay increased mainly because the field losses were reduced due to less of the hay getting wet. The harvesting time remained almost constant. At a lower probability value wetting of hay due to rain prolonged the hay-making season. At a higher probability value there was less opportunity for the hay to get wet but the crop was not cut on certain days on which it would otherwise had have been at a lower probability value; this resulted in a longer season.

10.2.2 Swath area limit

Figure 10.2 shows the effect of various swath area limits on the DDM yield of hay and on harvesting time. The DDM yield was lower for 1-day and 3-day limits compared to 2-day which suggests that the lower limit did not enable the farmer to finish his whole area and the higher limit put more crop at risk of adverse weather resulting in higher losses. The harvesting time decreased as the swath area limit increased because hay-making was carried out at a faster rate.

10.2.3 Maturity at the start of season

The pasture growth model presented in Chapter 4 does not predict the crop maturity directly, but it does predict the digestibility of pasture. As the pasture becomes mature the digestibility decreases, and this was used as a measure of maturity. The
**Policy Description**

- Digestibility at start of season = 0.70
- Swath area limit = 2-day
- Probability of 3 dry days = *

---

**Figure 10.1** Effect of weather prospects after cutting on DDM yield of hay and on harvesting time.
Policy Description

Digestibility at start of season = 0.61
Swath area limit = *
Probability of 3 dry days = 0.3

Figure 10.2 Effect of swath area limit on DDM yield of hay and on harvesting time.
maximum digestibility at or below which hay can be cut is given as an input. In the model, it is compared daily with the digestibility of standing pasture. If the digestibility of pasture is greater than the maximum digestibility, then the pasture is considered immature and cutting is postponed till it reaches the specified value.

The digestibility criterion was chosen in preference to a calendar date because the pasture could reach the same maturity level on different dates during different years. Table 10.3 shows the range of dates within which hay-making could be started at various maturity levels. There was a large year-to-year variation in the start date. For example for 16 years, it varied from 19 October to 14 November when the digestibility at the start of season was fixed at 0.64.

Table 10.3 Range of hay-making start dates for various maturity levels over 16 years.

<table>
<thead>
<tr>
<th>Digestibility at start of season</th>
<th>Start date</th>
<th>Earliest</th>
<th>Latest</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.70</td>
<td>1 October</td>
<td>27 October</td>
<td></td>
</tr>
<tr>
<td>0.67</td>
<td>6 October</td>
<td>5 November</td>
<td></td>
</tr>
<tr>
<td>0.64</td>
<td>19 October</td>
<td>14 November</td>
<td></td>
</tr>
<tr>
<td>0.61</td>
<td>27 October</td>
<td>24 November</td>
<td></td>
</tr>
<tr>
<td>0.58</td>
<td>3 November</td>
<td>3 December</td>
<td></td>
</tr>
</tbody>
</table>

The effect of digestibility at the start of season on the DDM yield of hay and on harvesting time is shown in Figure 10.3. The DDM yield increased when the season was started at 0.67 digestibility instead of 0.70 due to increased DDM of standing

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Policy Description

Digestibility at start of season = *
Swath area limit = 2-day
Probability of 3 dry days = 0.3

Figure 10.3 Average and range (± S.Dev.) of CDM yield of hay and harvesting time as a function of digestibility at the start of season.
pasture. However, below 0.67 digestibility the DDM yield did not increase at the same rate and rather decreased at 0.58 digestibility for two reasons:

(i) inability of the system to finish all the area before the end of the season, and

(ii) reduction in DDM yield of standing crop associated with drying off of the pasture.

The harvesting time decreased as the digestibility at the start of season was decreased because the hay-making was carried out in an improving weather regime.

The variability in DDM yield and harvesting time over the 16-year simulation period also is shown by the bars in the above figure. The variation in DDM yield was due not only to weather during harvest but also to the variability in DDM yield of standing crop due to seasonal growing conditions. However, the variation in harvesting time was largely due to weather during the hay-making season.

10.2.4 Optimum hay-making policy

The results presented in Sections 10.2.1 to 10.2.3 revealed that all the three factors, weather prospects after cutting, swath area limit and maturity at the start of season, affect the system's performance.

In order to identify the optimum combination of above factors for the given area and machinery system, a total of 45 policies
(Table 10.4) were investigated. Each policy was described by the digestibility at the start of season, the swath area limit and the probability of 3 dry days. For example, policy 1 means that hay-making can be started when the digestibility of standing crop is 0.70 or less, the crop should be cut on a given day if the probability of 3 dry days is at least equal to 0.3 and the cut crop lying in the swath is less than the 1-day harvest capacity of the system.

As an illustration, Figure 10.4 shows the effect of crop maturity at various swath area limits for a probability value of 0.3. It can be seen that a 1-day swath limit resulted in higher DDM yield of hay for an early maturity (higher digestibility at the start of season) whereas the 2-day and 3-day limits resulted in a higher DDM yield for a late maturity (lower digestibility at the start of season). This is due to the fact that if harvesting progresses at a very high rate in an early part of the season, then the system will harvest a large percentage of area with a lower DDM yield of standing crop, and also more area will be at risk of adverse weather at any given time. However, if a season is started late with a low crop digestibility, then the lower swath area limit will not allow the farmer to finish the whole area before the end of season resulting in a lower DDM yield of harvested hay.

The harvesting time decreased with an increase in swath area limit and/or decrease in digestibility at the start of season for the reasons explained in Sections 10.2.2 and 10.2.3.
Table 10.4  Hay-making policies investigated by the simulation model.

<table>
<thead>
<tr>
<th>Policy</th>
<th>Digestibility at start of season</th>
<th>Swath area limit (days of harvest)</th>
<th>Probability of 3 dry days</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.70</td>
<td>1</td>
<td>0.3</td>
</tr>
<tr>
<td>2</td>
<td>0.70</td>
<td>1</td>
<td>0.4</td>
</tr>
<tr>
<td>3</td>
<td>0.70</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>4</td>
<td>0.70</td>
<td>2</td>
<td>0.3</td>
</tr>
<tr>
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<td>0.70</td>
<td>2</td>
<td>0.4</td>
</tr>
<tr>
<td>6</td>
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<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td>7</td>
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<td>3</td>
<td>0.3</td>
</tr>
<tr>
<td>8</td>
<td>0.70</td>
<td>3</td>
<td>0.4</td>
</tr>
<tr>
<td>9</td>
<td>0.70</td>
<td>3</td>
<td>0.5</td>
</tr>
<tr>
<td>10</td>
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<td>1</td>
<td>0.3</td>
</tr>
<tr>
<td>11</td>
<td>0.67</td>
<td>1</td>
<td>0.4</td>
</tr>
<tr>
<td>12</td>
<td>0.67</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>13</td>
<td>0.67</td>
<td>2</td>
<td>0.3</td>
</tr>
<tr>
<td>14</td>
<td>0.67</td>
<td>2</td>
<td>0.4</td>
</tr>
<tr>
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</tr>
<tr>
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<td>0.3</td>
</tr>
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<td>3</td>
<td>0.4</td>
</tr>
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</tr>
<tr>
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<td>1</td>
<td>0.3</td>
</tr>
<tr>
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<td>0.64</td>
<td>1</td>
<td>0.4</td>
</tr>
<tr>
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<td>0.5</td>
</tr>
<tr>
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<td>0.3</td>
</tr>
<tr>
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<td>0.64</td>
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<td>0.4</td>
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</tr>
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</tr>
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</tr>
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<td>0.5</td>
</tr>
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<td>0.3</td>
</tr>
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<td>0.61</td>
<td>2</td>
<td>0.4</td>
</tr>
<tr>
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<td>2</td>
<td>0.5</td>
</tr>
<tr>
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<td>0.3</td>
</tr>
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</tr>
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</tr>
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</tr>
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</tr>
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</tr>
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</tr>
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<td>2</td>
<td>0.5</td>
</tr>
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<td>3</td>
<td>0.3</td>
</tr>
<tr>
<td>44</td>
<td>0.58</td>
<td>3</td>
<td>0.4</td>
</tr>
<tr>
<td>45</td>
<td>0.58</td>
<td>3</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Figure 10.4 Effect of digestibility at the start of season on DDM yield of hay and on harvesting time at various swath area limits.
Based on an average DDM yield of hay, policy 39 (digestibility at start of season = 0.61, swath area limit = 2-day and probability of 3 dry days = 0.3) was found to be the best, harvesting the hay with an average DDM yield of 1.39 t ha$^{-1}$ and finishing the harvest in 31 days. This illustrates the way in which the model can be used to investigate a number of policies and identify an optimum.

10.3 Hay-making Efficiency and Potential for Improvement

If there is an unlimited machinery capacity and sufficient drying potential of air, then theoretically all the area can be harvested instantaneously. Assuming also that there are no mechanical losses, then the potential DDM yield of hay will be equal to the maximum DDM yield of standing crop during the hay-making season. Hay-making efficiency, thus, can be defined as a ratio of DDM yield of hay actually harvested by a given system to the potential DDM yield.

Figure 10.5(a) shows hay-making efficiency for various conditions. For the given machinery system and area (medium system with 2 men and 50 ha), the efficiency was 64% when 3-day forecasts only were used to schedule cutting operation. The efficiency increased to 68% when the revised probability of 3 dry days was used instead of forecasts only. This indicates that the decision to cut based upon 3-day forecasts alone was correct less often than the decision based upon the combined information of forecasts and historical data. Hence, it is not advisable to consider only forecasts believing that this one piece of data
Figure 10.5 Hay-making efficiency and DDM yield of hay under various conditions.
provides as good a basis as any for making a weather sensitive decision such as hay-making.

It is not feasible to achieve 100% efficiency, but in order to identify a practical upper limit to hay-making efficiency, the simulation model was run using the same weather data file but rain was changed into no-rain. Under these conditions of no-rain, the efficiency increased to 80%.

The potential for increasing the DDM yield of hay is shown in Figure 10.5(b). By using better management techniques and having accurate long-term weather forecasts (greater than three days), it may be possible to harvest hay in a "no-rain" period and increase the DDM yield from 1.78 t DDM ha⁻¹ (3-day forecasts of present accuracy) to 2.25 t DDM ha⁻¹; this represents an increase of about 26%.

Hay-making efficiency and the DDM yield can be increased if the weather forecasts are 100% correct because they will enable the farmer to schedule the hay-making operations more efficiently. The model was run by assuming that weather forecasts were 100% correct. Compared to present accuracy of forecasts, the efficiency improved from 64 to 71% and the DDM yield of hay increased from 1.78 t ha⁻¹ to 1.97 t ha⁻¹, an increase of 11%.

The DDM yield of hay can also be increased by decreasing the drying time in the field, which in turn reduces losses due to adverse weather. There are a number of alternatives which can be used to reduce the field drying time:
(i) increasing the drying rate by conditioning of the crop at the time of cutting,

(ii) baling hay at a higher moisture content and treating it with preservatives, and

(iii) baling hay at a higher moisture content and drying it in the barn with unheated or heated air.

Barn drying of wet hay is unlikely to be an attractive alternative in Australia because of its high energy cost and labour requirements. The following sections investigate the feasibility of the other two alternatives outlined above.

10.3.1 Conditioning of crop at the time of cutting

Conditioning of a crop at the time of cutting increases the drying rate (Section 5.7) and reduces the number of days the cut crop remains in the field. This results in an increase in the DDM yield of hay due to a reduction of field losses.

The simulation model was used to determine the effect of three different drying rates on the DDM yield of hay and on harvesting time. Rates were 35, 70 and 100% higher than the drying rate of unconditioned hay which were expressed by exponents 0.45, 0.77 and 1.00 respectively for the term \((1+\text{COND})\) in Equation 5.15. The 35% increase in drying rate was found during the field drying experiments carried out by the author (Section 5.10). The higher rates were considered because there is a possibility of achieving such drying rates either through heavy mechanical conditioning or a combination of mechanical and chemical conditioning (Tullberg
et al., 1984).

Figure 10.6 shows the effect of increased drying rates on the DDM yield of hay and on harvesting time. Compared to the DDM yield of unconditioned hay, the DDM yield increased by 9, 13 and 15% for increases in drying rate of 35, 70 and 100%, respectively. The decreases in harvesting time were about 26, 29 and 32%, respectively.

Since there is an additional investment for the conditioner, this alternative should be used only if the extra cost due to conditioning is less than the value of increased DDM yield of hay. The present level of conditioning, which increased drying rate by 35%, resulted in an increase in DDM of 0.17 t ha⁻¹ which is equivalent to about 16 bales of hay per ha. Hence, the use of a conditioner is justifiable only if the difference in cost per ha of mowing and mowing-conditioning is less than the value of about 16 rectangular bales.

10.3.2 Baling hay at a higher moisture content

Hay is usually baled at a moisture content of about 25% (dry basis). If it is baled at values greater than this, biological activity causes heating which results in dry matter losses and a decrease in digestibility. However, the treatment of wet hay with a chemical preservative such as propionic acid or ammonium bispropanoate inhibits biological activity and allows the safe storage of hay baled at a higher than normal moisture content (Benham and Redman, 1980).
Figure 10.6 Effect of drying rate on DDM yield of hay and on harvesting time.
Baling and storing hay at higher moisture contents is beneficial because of a reduction in

(i) weather risk due to decreased drying time in the field, and
(ii) mechanical losses during raking and baling because these operations are then carried out at higher moisture contents when the crop is less susceptible to mechanical damage.

At present, there are problems in using hay preservatives such as non-uniform application, losses during application and uneven moisture content in the swath (Charlick et al., 1980; Lacey et al., 1980). Nevertheless, it is useful to investigate the potential benefit for hay baled at higher moisture contents. The simulation model, therefore, was run to compare the effects of baling at four other moisture contents: 33, 43, 54 and 67% (dry basis), with hay baled at 25%. As expected baling hay at higher moisture content increased the DDM yield and decreased the harvesting time (Figure 10.7). The DDM yield increased by 0.18, 0.28, 0.33 and 0.36 t DDM ha\(^{-1}\) by baling hay at 33, 43, 54 and 67% moisture content, respectively. The harvesting time decreased by 26, 36, 41 and 45%, respectively.

As there is a certain cost associated with the use of preservatives, baling hay at a higher moisture content will be beneficial only if the cost of applying a preservative is less than the gain in DDM yield of hay. Therefore, a cost analysis was carried out based on the application rates given in Table 10.5. The cost of propionic acid was taken as $1.5 kg\(^{-1}\) and the value of hay as $200.0 t\(^{-1}\) of DDM. The cost of the equipment for applying preservatives is likely to be small (Parke and Dumont,
Figure 10.7 Effect of moisture content at baling on DDM yield of hay and on harvesting time.
1976) compared to the cost of preservative and hence this cost was not considered.

<table>
<thead>
<tr>
<th>Moisture content (%)</th>
<th>Application rate (kg t(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry basis</td>
<td>Wet basis</td>
</tr>
<tr>
<td>25 - 33</td>
<td>20 - 25</td>
</tr>
<tr>
<td>33 - 43</td>
<td>25 - 30</td>
</tr>
<tr>
<td>43 - 54</td>
<td>30 - 35</td>
</tr>
<tr>
<td>54 - 67</td>
<td>35 - 40</td>
</tr>
</tbody>
</table>

The effect of moisture content at baling on return due to increased DDM yield and on the cost of preservative is shown in Figure 10.8. The net benefit (return on increased DDM yield of hay minus the cost of preservative) was negative at all moisture contents because the cost of preservative was higher than the value of increased DDM yield. The difference in cost and return increased as the moisture content at baling increased. This happened because the relative increase in DDM yield was less than the increased application rate of preservative. A different conclusion would be reached if the relative price of preservative and hay were to change.

10.4 Effect of System Capacity

The comparative performance of three different systems, small, medium and large, described in Section 10.1.1, was investigated for the 50 ha crop and two-man farm.
Figure 10.8 Effect of moisture content at baling on return and preservative cost.
Figure 10.9 shows how the DDM yield of hay and the time to finish harvest varied from system to system. The DDM yield harvested by a small system was much lower than the medium and large systems because large percentages of area remained unharvested by the end of season due to the small machinery capacity. Also on many occasions it was not possible to bale all the hay when it first reached the baling moisture content which resulted in higher losses due to prolonged exposure to weather. Compared to the medium system, the DDM yield decreased by 21% for the small system, and increased by 3% for the large.

The harvesting time decreased with the increase in system capacity. For example, the large and medium systems harvested a 50 ha crop in 58% and 82% respectively of the time required for the small system.

10.5 Effect of Manpower

Figure 10.10 shows the effect of manpower on DDM yield of hay and on harvesting time. The extra manpower was used only for the carting operation. Raising manpower from 2 to 3 increased the DDM yield by 1.5%. However, when the manpower was increased from 3 to 4, the increase in DDM yield was negligible. The harvesting time remained almost the same for all the cases because during hay-making it was the weather and not the shortage of labour which limited the progress of hay-making.
Figure 10.9 Effect of system capacity on DDM yield of hay and on harvesting time.
Figure 10.10 Effect of manpower on DDH yield of hay and on harvesting time.
10.6 Hay-making Systems and Crop Area

The three hay-making systems described earlier also were used to simulate hay-making for different crop areas. No attempt was made to determine the optimum policy for each combination of area and machinery system. The simulations were made by following the optimum policy as determined for the medium system (Section 10.2.4). Figure 10.11 shows how the DDM yield and harvesting time varied with area for various systems. As the system capacity was increased the DDM of hay increased for a given area. The harvesting time was higher for a large area and it decreased with the increase in system capacity for all the areas.

The efficiency of hay-making (Section 10.3) and area completed are shown in Figure 10.12. With an increase in system capacity, the hay-making efficiency increased for all areas. There was little difference in efficiency for an area of 20 ha, but when the area was more than 20 ha there were large differences between the various systems. This occurred mainly because the small and medium systems were unable to finish all the area by the end of season.

Based purely on DDM of hay and area completion, it appears that the small system is suitable up to 20 ha, the medium system between 20-50 ha, and the large system for an area greater than 50 ha. However, the detailed selection of a system for a given area would require comparison of the cost of hay production or more precisely the net return for each system.
Figure 10.11 DDM of hay and harvesting time as a function of area for various hay-making systems.
Figure 10.12 Hay-making efficiency and area completed by various hay-making systems.
10.7 Bay Quality and Start of Season

In Section 10.1.1, it was assumed that cutting would be allowed as long as the digestibility of standing pasture did not fall below 50%. For animals demanding high quality hay, the required minimum digestibility limit may be higher, say 55%. Hence, simulations were carried out for different starting digestibilities to determine the optimum value at the start of season for high quality hay.

The DDM yield increased when the digestibility at the start of season was increased, but starting the season too early resulted in lower DDM yield (Figure 10.13). The optimum starting digestibility for the given area and machinery system (50 ha, medium system and 2 men) was found to be 0.67 for high quality hay instead of 0.61 for low quality (Section 10.2.4). Since, the digestibility of growing pasture decreases at the rate of about 0.02 per week (Table 10.3), hay-making should start about 3 weeks earlier if high quality hay is required.

The optimum DDM yield decreased from 1.89 t ha\(^{-1}\) (lowest digestibility = 0.50) to 1.76 t ha\(^{-1}\) (lowest digestibility = 0.55). This occurred because most hay was cut during the period when the DM yield was lower. The harvesting time in the latter case increased by about a week due to the fact that hay-making was carried out during less favourable weather.
Figure 10.13 Effect of digestibility at the start of season on DDM yield and on harvesting time for high quality hay (minimum digestibility = 0.55).
10.8 Management of Hay-making Operations

To give a summary of management of hay-making operations, the simulations were made for one season using the same machinery capacity and hay-making policy. The weather data and a sequence of random numbers for generating weather forecasts also were identical.

Figure 10.14 shows the differences in progress of hay-making between an unconditioned and a conditioned system. As expected, hay-making was carried out at a faster rate when the pasture was conditioned at the time of cutting. This is clear from the histograms which show that, compared to unconditioned hay, it was always possible to perform harvesting operations earlier when hay was conditioned. The conditioned system took only 19 days to complete the harvest whereas the unconditioned system required 26 days.

Detailed examination of hourly results revealed that many times it was feasible to perform operations when it had rained on a given day (09.00 - 09.00 h on the next day). This happened because there was either no rain during the working period or it rained during only a part of the working period. For example, it is also evident from the results shown in Figure 10.14 where both the baling and the carting operations were carried out on the 9th day of the season when 14 mm rain fell. Hence, a daily rainfall criterion as used by some research workers (Cloud et al., 1968; Cunney and Von Bargen, 1974; Russell et al., 1983; Savoie, 1982) in the past is not sufficient to schedule hay-making operations.
Figure 10.14 Day-to-day progress of hay-making for unconditioned and conditioned systems.
The progress of hay-making for two and three-man operations is shown in Figure 10.15. As described earlier (Section 10.5), the third man was used only during the carting operation. The harvesting time for both these cases was identical. However, with a three-man operation, hay was carted on some days when it was not possible to cart hay with a two-man operation.

10.9 Sensitivity Analysis

In the simulation model, information on a number of hay loss parameters was scanty and in certain cases estimates had to be made. A sensitivity analysis was therefore used to identify parameters which have a large effect on the results; research can then be carried out in future to improve the estimation of such parameters. To test the sensitivity of the model, the following formula, similar to the one developed by Ng and Loomis (1984), was used:

$$S = \frac{(NV - CV) \times 100}{CV}$$

(10.1)

where $S$ = sensitivity of output to a change in value of an input variable,

$NV$ = new value of output with a changed value of the input variable,

$CV$ = value of output in the control simulation run, and

$PCI$ = per cent change in value of the input variable.
Figure 10.15 Day-to-day progress of hay-making for a two-man and three-man farm.
According to Equation 10.1, the sensitivity measure is an elasticity, in this case, the percentage change in the output from that of the control simulation resulting from a one per cent change in an input value. For example, a sensitivity of +0.1 means that for each per cent increase in a particular input, the output increases by 0.1%.

The following five input variables were altered, one at a time:

(i) cutting loss,
(ii) raking loss,
(iii) baling loss,
(iv) respiration loss, and
(v) leaching loss.

Each input parameter was altered by +50% and -50% which resulted in a total of 10 sensitivity simulations. Since all the above factors affect the DDM yield of hay and not the harvesting time, the sensitivity measures were determined for this output variable only. The analysis results given in Table 10.6 show that the output is most sensitive to loss factors such as respiration and leaching which are dependent upon weather. Baling and raking losses are next, while cutting loss had the lowest sensitivity. It may be noted that although the changes in input were symmetrical (+50%), the absolute values of the sensitivities differed between the two directions of change due to the interaction of many non-linear relationships used in the simulation model.
Table 10.6  Ranking of input variables according to sensitivity measure.

<table>
<thead>
<tr>
<th>Input variable</th>
<th>Change</th>
<th>Absolute value of sensitivity</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-50%</td>
<td>0.150</td>
<td>1</td>
</tr>
<tr>
<td>Respiration loss</td>
<td>+50%</td>
<td>0.140</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>+50%</td>
<td>0.055</td>
<td>3</td>
</tr>
<tr>
<td>Leaching loss</td>
<td>-50%</td>
<td>0.051</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>+50%</td>
<td>0.036</td>
<td>5</td>
</tr>
<tr>
<td>Salting loss</td>
<td>-50%</td>
<td>0.023</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>-50%</td>
<td>0.022</td>
<td>7</td>
</tr>
<tr>
<td>Raking loss</td>
<td>+50%</td>
<td>0.021</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>+50%</td>
<td>0.015</td>
<td>9</td>
</tr>
<tr>
<td>Cutting loss</td>
<td>-50%</td>
<td>0.011</td>
<td>10</td>
</tr>
</tbody>
</table>
CHAPTER 11

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

A simulation model of hay-making in southern Australia was developed to evaluate alternative machinery systems and management policies in terms of digestible dry matter (DDM) yield of hay and of harvesting time. Alternative hay-making policies were represented by weather prospects after cutting, maximum cut crop allowed in the swath, and maturity at the start of the season. The effects of the following factors on the performance of the system also were investigated:

(i) conditioning the crop at the time of cutting,
(ii) baling hay at higher moisture contents and treating it with a preservative,
(iii) accurate weather forecasts,
(iv) system capacity, and
(v) manpower.

11.1 General Conclusions

The hay-making processes involve highly complex interactions between the biological crop material, the environment and the machines. They also involve a series of intuitive management decisions, the modelling of which is likely to be, at best, a crude approximation.
The simulation technique provided a method for simultaneously considering the inter-related aspects of the hay-making processes such as pasture growth, weather, machinery and management of operations. It also enabled analysis of a much wider range of hay-making systems than would be possible in the few field experiments which could be completed in one season. Also the hay-making simulation model can be extended to other climatic conditions and to investigation of the usefulness of new technologies.

The accuracy of the model, at an absolute level, is not known but it does provide a better understanding of the relative importance of various factors. For example, it showed that accurate weather forecasts were likely to produce more benefit \((\Delta DDM)\) compared to very large machinery capacity and manpower. Further, the year-to-year variation in DDM yield of harvested hay was due not only to weather during harvest but also to the variability in DDM yield of standing pasture due to seasonal growing conditions. This indicates that both the management of the growing pasture and that of hay-making operations are important if the production is to be maximized.

It would be desirable to know how closely the simulation results obtained from this study compare with actual results achieved on farms. Unfortunately, there were no adequate experimental data against which the results could be validated. The swath hay drying model was tested and it was found to give a good agreement between the observed and predicted moisture contents. No detailed information on hay losses and corresponding weather data...
were available to validate the hay loss model. However, the average losses seem to be in general agreement with those reported in the literature (Cameron, 1966; Simmons, 1981).

The overall conclusions from this study are that to achieve a significant increase in DDM yield of hay, either an improvement in weather forecast accuracy (preferably for more than three days) is necessary or the drying time in the field must be reduced by applying a treatment such as conditioning of the crop at the time of cutting. The development of this simulation model has not only highlighted the need for more data but has provided a reason for its collection; a sound base of experimental data, especially related to losses during hay-making, is essential to compare the performance of hay-making systems.

11.2 Specific Conclusions

Based on the historical weather data from Laverton, Victoria, the following specific conclusions may be drawn.

(i) All the management factors such as weather prospects after cutting, maximum cut crop allowed in the swath and maturity at the start of season affect the DDM yield of hay and the harvesting time. However, maturity at the start of season is the most important of these factors. Starting the season too early or too late results in lower DDM yield. At the present level of accuracy of weather forecasts, a farmer has to take a certain risk (with respect to the weather forecast and maximum cut crop allowed in the swath) at the
time of cutting in order to achieve maximum possible DDM yield and also finish the harvest in a reasonable period. A conservative policy results in a longer harvest period whereas an aggressive one finishes the harvest in a shorter period. A highly conservative or too aggressive policy would result in lower DDM yield. There exist various optimum combinations of the above factors for each farm situation (area and machinery capacity) which would yield near maximum DDM.

(ii) The use of three-day forecasts alone is not sufficient for optimum scheduling of hay cuts. Decisions based on the historical probability of three dry days and on forecasts, are more beneficial as these would result in about a 6% increase in DDM yield. If farmers could be provided with 100% accurate three-day forecasts, an increase of 11% in DDM yield could be expected. Accurate long-term weather forecasts (more than three days) and better management techniques, which would avoid hay being wet, would increase the DDM yield by 26%.

(iii) The DDM yield of hay can also be increased by decreasing the drying time in the field by conditioning the crop at the time of cutting. Conditioning of a crop, which raises the drying rate by 35%, could increase the DDM yield by about 10% and decrease the harvesting time by 25%. However, the use of a conditioner is economically justifiable only if the difference in cost per hectare of mowing and mowing-conditioning is not more than the value
of about 16 bales of hay. A further increase in drying rate either by heavy conditioning or a combination of mechanical and chemical conditioning will also increase the DDM yield and decrease the harvesting time.

(iv) Baling hay at higher moisture contents is another alternative which can be used to reduce the drying time. As the moisture content at baling increases, the DDM yield increases and harvesting time decreases. For example, if hay is baled at a moisture content of 33% (dry basis) instead of the usual 25%, a 10% increase in DDM yield and a 30% decrease in harvesting time may be expected. However, when hay is baled at a higher than normal moisture content, it must be treated with a preservative such as propionic acid to prevent its spoilage in storage. At the present cost structure of acid and hay, this alternative is unlikely to be economically feasible in this region of Australia.

(v) Increasing the manpower from 2 to 3 results in an increase of 1.5% DDM yield of hay; a further increase in manpower provides little benefit. The harvesting time is likely to remain constant because frequently it is the weather, and not the shortage of labour, which delays the progress of hay-making.

(vi) For animals demanding high quality hay, hay-making should start early when the digestibility of growing pasture is still high. For example, if the required minimum
digestibility limit is 0.55, the season should start when the digestibility is about 0.67. For lower quality hay (minimum digestibility = 0.50), the start of season may be delayed till the digestibility reaches 0.61 which represents a delay of about three weeks.

(vii) Increasing the system capacity will increase the DDM yield and decrease the harvesting time. However, to justify the purchase of large machinery, the relative increase in hay value must be assessed against the increased capital cost. The hay-making efficiency of a given system decreases as the crop area to be harvested increases, mainly due to the area which remains unharvested at the end of season. It also decreases with the decrease in system capacity. Based purely on DDM yield and area of completion, a small system (as defined in Table 10.2) is feasible up to 20 ha, a medium system between 20-50 ha, and a large system for an area greater than 50 ha. However, detailed selection of a system for a given area should be based on cost of hay production or net return for each system.

11.3 Recommendations for Future Research

With the exception of the hay drying model, the simulation is based largely on research data published in the literature. There are, therefore, some weaknesses in the model which could be reduced if data from more field experiments were available. In addition the model has a great potential for evaluating hay-making systems and management policies under other climatic
conditions. In this section, recommendations for future research, to extend the use of the present model and to make improvements in it, are given.

11.3.1 Wider application of the model

The results presented in Chapter 10 and conclusions drawn in Sections 11.1 and 11.2 are based on the weather data from only one meteorological station. The effects of management policies and new technologies on the performance of each system should be investigated by employing meteorological data from other parts of Australia. For example, baling hay at higher moisture contents and treating the hay with a preservative was not found to be economical in this region. However, it would be useful to identify weather/rainfall patterns under which this practice would become profitable.

In this study, the DDM yield of hay was used as a major criterion for comparing the performance of systems. However, the hay-making model could be linked with a whole farm model incorporating the feeding of dairy or beef cattle or sheep. This would enable a more objective comparison of the net return from each machinery system which in turn could be used as a basis of selection of an optimum hay-making system for a given farm. Such an exercise also would require estimates of the cost of hay production and feeding, and prediction of income from animal produce such as milk, meat and wool.
11.3.2 Collection of more data

Major limitations of the present model are lack of data, especially the information related to losses during hay-making. The sensitivity analysis showed the extent to which loss parameters affected the performance of the system studied. Further experiments also are required to refine the hay drying models. Consequently, more research should be carried out in the following areas:

(i) Parameters defining losses due to environmental factors and mechanical operations should be refined by carrying out field experiments. Little is known about the dry matter loss due to respiration of wet hay during the field drying process. Leaching loss data are scanty and experiments are needed to determine the effect of the moisture content of hay and different quantities of rain on this loss. The effect of moisture content, speed of operation and yield on mechanical losses, especially during raking and baling operations, should be investigated. Separate determination of loss of leaves and stems is desirable to accurately estimate the change in quality of hay.

(ii) Field experiments should be carried out to validate the present baled hay drying model, especially the increase in moisture content due to rain which in this work was estimated theoretically. A similar model also is required for large round bales.
(iii) In the present swath hay drying model, the raking operation was simulated by inversion of samples in the drying trays. A separate drying model for raked hay should be developed by performing the actual raking operation at different times during the drying cycle. Such a model would be helpful in assessing the effects of early and late raking on the performance of the system.

(iv) Field-drying experiments showed that there was a large variation in the moisture content of swath from top to bottom. Further experiments should be conducted to determine the moisture content of different layers in the swath for a range of pasture yields. Such an information would be useful to simulate the drying process more adequately.

(v) Theoretical field capacities of hay-making equipment quoted by the manufacturers are higher than can be achieved in practice over long periods. Field experiments are required to arrive at the actual field capacities for each hay-making operation.

11.3.3 Refinement of sub-models

The various sub-models included as much detail as was deemed necessary to reasonably simulate the hay-making process. However, the sub-models are not definitive; much research could still go into their improvement. Long term research should be directed towards the following:
(i) Development of a pasture growth model which could predict changes in yield, digestibility and moisture content on a daily basis. The estimation of these parameters for leaves and stems separately is essential for more accurate determination of mechanical losses during hay-making. The model should also be able to estimate the re-growth of pasture after cutting so that this aspect also could be considered in comparing the performance of alternative systems.

(ii) Only one closure date for the whole pasture area was considered in the simulation model. However, the yield and digestibility of growing pasture vary with the closure date, so that if paddocks reach maximum DDM at different times during the season, hay could be harvested from each paddock at close to the optimum time. It would be worthwhile to determine what effect this practice would have on the total DDM from a given area.

(iii) In the present management model a fixed management policy in regard to weather prospects after cutting and swath area limit was specified for the whole season. The management model could be modified to incorporate a variable policy, e.g., changing minimum revised probability of three dry days and the swath area limit as the season progresses. The effect of this on the performance of the systems should be investigated.
(iv) The weather forecast model in the present simulation considered only "rain" and "no-rain" criteria. Efforts should be directed to make use of other weather parameters such as the maximum and minimum temperatures, which are now predicted by the Bureau of Meteorology for two or three days. Ideally, there is a need to develop a method which could make use of these parameters to predict, at the time of cutting, whether the hay can be harvested without being rained on or not.

The work reported in this thesis provides a basis for further development of the model as well as justification and guidance for further data collection. It is only a beginning and in no way does it provide final answers to the problems raised. We still have to go a long way to fulfill the dream to "make hay while the sun shines".
REFERENCES


Fuller, E.I., 1969. The extension uses and limitations of a forage harvest simulator. Dept. of Agric. and Food Econ., Univ. of Massachusetts, Amherst, Massachusetts, USA.


APPENDICES
The simulation program HAYSIM is written in the FORTRAN-77 language and implemented on the Vax 11/780 computer at the University of Melbourne. A memory of 100K bytes is required to compile and execute the program. The time required to complete 16 years of simulation (with 5 replications in each year) is about 2.5 min on the Vax 11/780 and 50 sec on the Vax 8650. The listing of the program and a sample output are presented in the following pages.
LISTING OF THE COMPUTER PROGRAM HAYSIM

PROGRAM HAYSIM
C
THIS PROGRAM SIMULATES THE HAY-MAKING SYSTEMS
C
WRITTEN BY : M.L. GUPTA, AGRIC. ENG. SECTION, DEPT. OF
C
CIVIL AND AGRIC. ENG., UNIV. OF MELBOURNE.
COMMON/B1/ NDAYS, IWTYPE, DATE(100), RAIN(100), VPEN(100),
1 RN(100), TN(100), VP(100,20), W(100,20),
2 RS(100,20), R(100,20), T(100,20)
COMMON/B2/ IDAY, AREAL, NP(4), LDAJX, MAN, MNT, HR(4), NM(4), NT(4),
1 IHD, RMC, LMC, RP(8), AR(4,200), XMC(4,200),
2 YD(4,200), TOP(4), ICART, NOP, ARE, ISAL, DSTMIN, DSTMAX
COMMON/B3/ YIELD, DIGEST, XIMC, DST(4,200), CRAIN(3,200),
1 RNIN(3,200), XMIMC(3,200), TRAIN(3,200), ASSTORE
COMMON/B4/ IHOUR, ICOND, IBALE
COMMON/B5/ IYEAR, NS(25), AREA, IDAYB
COMMON/B6/ LP
COMMON/B7/ NYEARS, NREP, IREP
COMMON/B8/ AST(25,10), AUF(25,10), AUCT(25,10),
1 ASWATH(25,10), ABALE(25,10), DM(25,10),
2 DDM(25,10), IHDAYS(25,10)
COMMON/B9/ ISEED
COMMON/B10/ ACUT(100), ARAK(100), ABAL(100), ACAR(100), TCUT(100),
1 TRAK(100), TBAL(100), TCAR(100)
COMMON/B11/ PCCL, PCRKL, PCBL, PCLR, PCLL
CHARACTER DATE*6
C
OPEN (UNIT=1, FILE='HAYSIM.DAT', STATUS='OLD', DISPOSE='SAVE')
OPEN (UNIT=2, FILE='WEATHER.DAT', STATUS='OLD', DISPOSE='SAVE')
OPEN (UNIT=3, FILE='HAYSIM1.OUT', STATUS='NEW', DISPOSE='SAVE')
OPEN (UNIT=4, FILE='HAYSIM2.OUT', STATUS='NEW', DISPOSE='SAVE')
OPEN (UNIT=5, FILE='HAYSIM3.OUT', STATUS='NEW', DISPOSE='SAVE')
C*****READ SYSTEM INPUT DATA
C AREA = TOTAL CROP AREA FOR HAYMAKING, HA
C MAN = TOTAL NUMBER OF MEN AVAILABLE FOR HAYMAKING
C ICOND= TYPE OF HAY, 0=UNCONDITIONED, 1=CONDITIONED
C IBALE= TYPE OF BALES, 1=RECTANGULAR, 2=ROUND
C ICART= INDICATOR FOR CARTING OPERATION
C 0 = NO CARTING, BALES STORED IN THE FIELD
C 1 = CONTRACT CARTING
C 2 = CARTING TO BE DONE BY ON FARM LABOUR
READ (1,*) AREA, MAN, ICOND, IBALE, ICART
C NIT = TOTAL NUMBER OF TRACTORS AVAILABLE
C WR(I) = WORK RATE OF ITH OPERATION
C CUTTING & RAKING, UNITS = HA/HR
C BALENG & CARTING, UNITS = T/HR
C NM(I) = NUMBER OF MEN REQUIRED FOR ITH OPERATIN
C NT(I) = NUMBER OF TRACTORS REQUIRED FOR ITH OPERATION
C (OPERATION 1 TO 4 ARE CUTTING, RAKING, BALENG & CARTING)
READ (1,*) NIT
C SET THE NO. OF OPERATIONS
IF (ICART .EQ. 2) THEN
  NOP = 4
ELSE
  NOP = 3
ENDIF
DO 400 I = 1,NOP
READ(1,*) WR(I),NM(I),NT(I)
CONTINUE

400

NYEARS = TOTAL NUMBER OF YEARS OF WEATHER DATA
NDAYS = NUMBER OF DAYS OF WEATHER DATA FOR EACH YEAR
IWTYPE = WEATHER DATA TYPE
  1 = HOURLY DATA INCLUDE VAPOUR PRESSURE DEFICIT, RAIN AND TEMPERATURE
  2 = HOURLY DATA INCLUDE VAPOUR PRESSURE DEFICIT, RADIATION, RAIN AND TEMPERATURE
  3 = HOURLY DATA INCLUDE VAPOUR PRESSURE DEFICIT, RADIATION, WIND SPEED AND TEMPERATURE.
NREPL = NUMBER OF REPLICATIONS TO BE MADE FOR EACH YEAR'S WEATHER DATA. EACH REPLICATION USES A DIFFERENT SEQUENCE OF NUMBERS FOR THE PURPOSE OF MAKING WEATHER FORECASTS.
READ(1,*) NYEARS,NDAYS,IWTYPE,NREPL

INT = INTERVAL OF TIME FOR MAKING NEW PLAN OF OPERATIONS
IHD = WORKING HOURS PER DAY FOR BALER
READ(1,*) INT,IHD

RKMC = MAX. MOISTURE CONTENT FOR RAKING OPERATION, % DB
BLMC = MAX. MOISTURE CONTENT FOR BALING OPERATION, % DB
READ(1,*) RKMC,BLMC

DSTMAX = MAXIMUM DIGESTIBILITY OF STANDING PASTURE AT THE START OF SEASON.
DSTMIN = MINIMUM DIGESTIBILITY BELOW WHICH CUTTING IS STOPPED
ARP = ACCEPTABLE REVISED PROBABILITY OF 3 DRY DAYS
ISAL = SWATH AREA LIMIT (NO. OF DAYS OF HARVEST CAPACITY)
READ(1,*) DSTMAX,DSTMIN,ARP,ISAL

PCCL = PERCENT CHANGE IN CUTTING LOSS
PCRKL= PERCENT CHANGE IN RAKING LOSS
PCBL = PERCENT CHANGE IN BALING LOSS
PCRL = PERCENT CHANGE IN RESPIRATION LOSS
PCLL = PERCENT CHANGE IN LEACHING LOSS
READ(1,*) PCCL,PCRKL,PCBL,PCRL,PCLL

ISEED = A VALUE OF LARGE CDD INTEGER TO INITIALIZING THE RANDOM NUMBER GENERATOR.
READ(1,*) ISEED

LP = LEVEL OF RESULTS FOR PRINTING
  1 = PRINT DETAILED RESULTS (HOUR BY HOUR)
  2 = PRINT SUMMARY RESULTS FOR EACH DAY DURING THE SEASON
  3 = PRINT SUMMARY RESULTS FOR EACH YEAR & REPLICATION
  4 = PRINT SUMMARY RESULTS FOR ALL YEARS
READ(1,*) LP

IYEAR = 0
CONTINUE
C*****PROCEED FOR NEXT YEAR
IYEAR = IYEAR + 1
IF(IYEAR .GT. NYEARS) GO TO 30
IF(LP .EQ. 1) WRITE(4,800) IYEAR
800 FORMAT('1'/10X,'DetaIed results of Hay Simulation Model'/
/25X,'YEAR = ',I2)
C*****READ WEATHER DATA FOR THIS YEAR
CALL WEATHER
IREPL = 0
7 CONTINUE
C*****PROCEED FOR NEXT REPLICATION
IREPL = IREPL + 1
IF(IREPL .GT. NREPL) GO TO 5
C*****INITIALIZE THE STATUS OF HAYMAKING AT THE START
C OF EACH REPLICATION.
C AREAI = AREA YET TO CUT, HA
C ASTORE= AREA IN STORE, HA
C NP(1) = NO. OF PLOTS IN FIRST STATE OF CROP (CUT CROP BUT
C UNRAKED).
C NP(2) = NO. OF PLOTS IN SECOND STATE OF CROP (RAKED CROP)
C NP(3) = NO. OF PLOTS IN THIRD STATE OF CROP (BALED HAY
C IN THE FIELD)
C NP(4) = NO. OF PLOTS IN FOURTH STATE OF CROP (BALED HAY
C IN THE STORE).
SAMPLE = AREA
ASTORE = 0.0
NP(1) = 0
NP(2) = 0
NP(3) = 0
NP(4) = 0
IDAY = 0
ISTART = 0
ILAST = 0
10 CONTINUE
C*****PROCEED FOR NEXT DAY
IDAY = IDAY + 1
C*****DETERMINE YIELD, DIGESTIBILITY AND INITIAL MOISTURE
C CONTENT OF STANDING CROP ON THIS DAY.
CALL PASTURE(IYEAR,IDAY,YIELD,DIGEST,XIMC)
C*****DETERMINE THE POSSIBLE START DATE (NS) BASED ON MAXIMUM
C LIMIT TO THE DIGESTIBILITY OF STANDING PASTURE.
IF(ISTART .EQ. 0) THEN
  IF(DIGEST .LE. DSTMAX) THEN
    NS(IYEAR) = IDAY
  ELSE
    ISTART = 1
  END IF
ELSE
  GO TO 10
ENDIF
ENDIF
C*****DETERMINE THE LAST DAY OF CUTTING (LDAYC) BASED ON MINIMUM
C DIGESTIBILITY OF STANDING PASTURE.
IF(ILAST .EQ. 0) THEN
  IF(DIGEST .LT. DSTMIN) THEN
    LDAYC = IDAY - 1
  ELSE
    LDAYC = NDAYS
  END IF
ELSE
  LDAYC = NDAYS
ENDIF
ENDIF
C*****INITIALIZE THE AREA CUT, RAKED, BAIEd AND CARTED FOR THIS DAY
ACUT(IDAY) = 0.0
ARAK(IDAY) = 0.0
ABAL(IDAY) = 0.0
ACAR(IDAY) = 0.0
C****** INITIALIZE THE TIME SPENT FOR CUTTING, RAISING, BALEING AND CARTING FOR THIS DAY
TCUT(IDAY) = 0.0
TRAC(IDAY) = 0.0
TBAL(IDAY) = 0.0
TCAR(IDAY) = 0.0
C****** DETERMINE THE ACTUAL STARTING DAY OF HAYMAKING (IDAYB)
IF(NP(1).EQ. 0) IDAYB = IDAY
IF(IDAY .GT. NDAYS) THEN
   CALL ENDR
   GO TO 7
ENDIF
IF(LP .EQ. 1) WRITE(4,805) DATE(IDAY)
805 FORMT(//25X,'DATE = '',A6)
IHOUR = 6
12 CONTINUE
IHOUR = IHOUR + 1
IF(LP.EQ.1 .AND. NP(1).GE.1) THEN
   WRITE(4,806) IHOUR,R(IDAY,IHOUR),VPD(IDAY,IHOUR),
   1         RG(IDAY,IHOUR),T(IDAY,IHOUR)
806 FORMT(//20X,'HOUR = ',I2/5X,'RAIN = ',F6.2,3X,
   1 'VPD =',F5.3,3X,'RG =',F5.3,3X,'TEMP =',F6.2)
ENDIF
CALL STATUSHOUR
IF(IHOUR .LT. 9) GO TO 12
C
C****** MAKE A WEATHER FORECAST FOR 3 DAYS AND REVISE THE PROBABILITIES OF OCCURRENCE OF DIFFERENT TYPES OF 3-DAY WEATHER
CALL FORECAST(IDAY,RAIN(IDAY),RAIN(IDAY+1),RAIN(IDAY+2),
   1 RP)
C
15 CONTINUE
C****** PLAN THE OPERATIONS FOR A GIVEN INTERVAL OF TIME CALL MANAGEMENT
C
C SET THE FLAG VALUE FOR DECISION OF NEW PLAN
IFLAG = 0
20 CONTINUE
C****** PROCEED FOR NEXT HOUR
IHOUR = IHOUR + 1
IF(IHOUR .GT. 20) THEN
   CALL STATUSNIGHT
   GO TO 10
ELSEIF(IHOUR .EQ. 14 .OR. R(IDAY,IHOUR) .GT. 0.0) THEN
   IF(LP.EQ.1 .AND. NP(1).GE.1) THEN
      WRITE(4,806) IHOUR,R(IDAY,IHOUR),VPD(IDAY,IHOUR),
      1         RG(IDAY,IHOUR),T(IDAY,IHOUR)
806 FORMT(//20X,'HOUR = ',I2/5X,'RAIN = ',F6.2,3X,
      1 'VPD =',F5.3,3X,'RG =',F5.3,3X,'TEMP =',F6.2)
   ENDIF
   CALL STATUSHOUR
   GO TO 25
ELSE
   IF(LP.EQ.1 .AND. NP(1).GE.1) THEN
      WRITE(4,806) IHOUR,R(IDAY,IHOUR),VPD(IDAY,IHOUR),
      1         RG(IDAY,IHOUR),T(IDAY,IHOUR)
ENDIF
    CALL OPERATIONS
    CALL STATUSHOUR
    IFLAG = IFLAG + 1
ENDIF

C*****STOP THIS YEAR'S SIMULATION IF ALL THE AREA IS HARVESTED
IF(ABS(AREA-ASTORE) .LT. 0.05) THEN
    CALL ENDRYR
    GO TO 7
ENDIF

C*****STOP THIS YEAR'S SIMULATION IF THE LAST DAY OF CUTTING IS
C PASSED AND THERE IS NO CROP LYING IN THE FIELD.
C ALF = AREA LYING IN THE FIELD (HA)
ALF = 0.0
DO 420 I = 1,3
    DO 415 J = 1, NPI(I)
        ALF = ALF + AR(I,J)
415    CONTINUE
420    CONTINUE
    IF(IDAY .GT. LDAYC .AND. ALF .EQ. 0.0) THEN
        CALL ENDRYR
        GO TO 7
    ENDIF
25    CONTINUE

C*****PREPARE A NEW PLAN OF OPERATIONS, IF REQUIRED.
    IF(R(IHOUR) .GT. 0.0) GO TO 15
    IF(IHOUR .EQ. 13) GO TO 20
    IF(IHOUR .EQ. 20) GO TO 20
    IF(IFLAG .EQ. INT) GO TO 15
    GO TO 20
30    CONTINUE

C*****WRITE THE SUMMARY RESULTS
    IF(LP .EQ. 3 .OR. LP .EQ. 4) CALL RESULT
    CLOSE(UNIT=1)
    CLOSE(UNIT=2)
    CLOSE(UNIT=3)
    CLOSE(UNIT=4)
    CLOSE(UNIT=5)
STOP
END

C***************************************************************************
SUBROUTINE WEATHER
C***************************************************************************
C THIS SUBROUTINES READS THE TRANSFORMED WEATHER DATA
C
          COMMON/BL/ NDIAS, IWTYPE, DATE(100), RAIN(100), VPDN(100),
               RN(100), TN(100), VPD(100,20), W(100,20),
               RG(100,20), R(100,20), T(100,20)
CHARACTER DATE*6
C
C VARIABLES USED ARE:
C DATE(J) = DATE ON JTH DAY
C NDIAS = NO. OF DAYS OF WEATHER DATA IN EACH YEAR
C R(J,K) = RAIN DURING KTH HOUR ON JTH DAY,MM
C RAIN(J) = RAIN DURING JTH DAY (9 A.M. TO 9 A.M.),MM
C RG(J,K) = GLOBAL RADIATION DURING KTH HOUR ON
C JTH DAY, MJ/M**2
C RN(J) = RAIN DURING JTH NIGHT,MM

218
T(J,K) = AVERAGE DRY BULB TEMPERATURE DURING KTH HOUR ON JTH DAY, DEG. C
TN(J) = AVERAGE DRY BULB TEMPERATURE DURING JTH NIGHT, DEG. C
VPD(J,K) = MEAN VAPOUR PRESSURE DEFICIT DURING KTH HOUR ON JTH DAY, KPA
VPDN(J) = AVERAGE HOURLY VAPOUR PRESSURE DEFICIT DURING JTH NIGHT, KPA
W(J,K) = WIND SPEED DURING KTH HOUR ON JTH DAY, M/S

DO 405 J = 1,NDAYS
READ (2,200) DATE(J),RAIN(J),VPDN(J),RN(J),TN(J)
200 FORMAT(1X,A6,5X,F6.2,5X,F5.3,2(5X,F6.2))
DO 400 K = 7,20
IF (IWTYPE .EQ. 1) THEN
READ(2,201) VPD(J,K),R(J,K),T(J,K)
ELSEIF (IWTYPE .EQ. 2) THEN
READ(2,202) VPD(J,K),RG(J,K),R(J,K),T(J,K)
ELSE
READ(2,203) VPD(J,K),RG(J,K),W(J,K),R(J,K),T(J,K)
ENDIF
201 FORMAT(8X,F5.3,2(5X,F6.2))
202 FORMAT(8X,F5.3,5X,F5.3,2(5X,F6.2))
203 FORMAT(8X,F5.3,5X,F5.3,3(5X,F6.2))
400 CONTINUE
405 CONTINUE
RETURN
END

**********************************************************************
SUBROUTINE PASTURE(IYEAR, IDAY, YIELD, DIGEST, XIMC)
**********************************************************************
C THIS SUBROUTINE DETERMINES THE YIELD, DIGESTIBILITY AND
C INITIAL MOISTURE CONTENT OF STANDING PASTURE ON ANY GIVEN
C DAY DURING THE HAIRMAKING SEASON.
COMMON/B6/ LP
C
C VARIABLES USED ARE:
C IYEAR = NUMBER OF YEAR
C IDAY = NUMBER OF DAYS AFTER 30 SEPTEMBER
C YIELD = DRY MATTER YIELD OF STANDING PASTURE, T/HA
C DIGEST = DIGESTIBILITY OF STANDING PASTURE, DECIMAL
C XIMC = INITIAL MOISTURE CONTENT, % DB
C
C*****DETERMINE YIELD AND DIGESTIBILITY ON THIS DAY
IF (IYEAR .EQ. 1) THEN
  YIELD = 2.187 + 0.0311*IDAY - 3.08E-04*IDAY**2
  DIGEST= 0.761 - 0.0068*IDAY + 4.28E-05*IDAY**2
ELSEIF (IYEAR .EQ. 2) THEN
  YIELD = 2.272 + 0.0509*IDAY - 4.43E-04*IDAY**2
  DIGEST= 0.779 - 0.0060*IDAY + 3.00E-05*IDAY**2
ELSEIF (IYEAR .EQ. 3) THEN
  YIELD = 2.443 + 0.0421*IDAY - 4.01E-04*IDAY**2
  DIGEST= 0.763 - 0.0055*IDAY + 2.35E-05*IDAY**2
ELSEIF (IYEAR .EQ. 4) THEN
  YIELD = 2.434 + 0.0936*IDAY - 7.90E-04*IDAY**2
  DIGEST= 0.755 - 0.0019*IDAY - 1.49E-05*IDAY**2
ELSEIF (IYEAR .EQ. 5) THEN
  YIELD = 2.055 + 0.0312*IDAY - 2.37E-04*IDAY**2

219
DIGEST = 0.757 - 0.0064*IDAY + 3.85E-05*IDAY**2
ELSEIF (IYEAR .EQ. 6) THEN
  YIELD = 2.231 + 0.0629*IDAY - 5.61E-04*IDAY**2
  DIGEST = 0.767 - 0.0048*IDAY + 1.56E-05*IDAY**2
ELSEIF (IYEAR .EQ. 7) THEN
  YIELD = 2.455 + 0.1199*IDAY - 10.24E-04*IDAY**2
  DIGEST = 0.782 - 0.0034*IDAY
ELSEIF (IYEAR .EQ. 8) THEN
  YIELD = 2.279 + 0.1322*IDAY - 10.86E-04*IDAY**2
  DIGEST = 0.784 - 0.0032*IDAY
ELSEIF (IYEAR .EQ. 9) THEN
  YIELD = 2.305 + 0.1285*IDAY - 10.86E-04*IDAY**2
  DIGEST = 0.786 - 0.0034*IDAY
ELSEIF (IYEAR .EQ. 10) THEN
  YIELD = 2.629 + 0.0396*IDAY - 3.21E-04*IDAY**2
  DIGEST = 0.785 - 0.0070*IDAY + 4.10E-05*IDAY**2
ELSEIF (IYEAR .EQ. 11) THEN
  YIELD = 2.430 + 0.0693*IDAY - 5.59E-04*IDAY**2
  DIGEST = 0.756 - 0.0026*IDAY - 8.05E-06*IDAY**2
ELSEIF (IYEAR .EQ. 12) THEN
  YIELD = 2.347 + 0.1187*IDAY - 9.72E-04*IDAY**2
  DIGEST = 0.784 - 0.0034*IDAY
ELSEIF (IYEAR .EQ. 13) THEN
  YIELD = 1.503 + 0.0673*IDAY - 4.92E-04*IDAY**2
  DIGEST = 0.684 - 0.0024*IDAY
ELSEIF (IYEAR .EQ. 14) THEN
  YIELD = 1.950 + 0.0412*IDAY - 2.88E-04*IDAY**2
  DIGEST = 0.737 - 0.0054*IDAY + 2.93E-05*IDAY**2
ELSEIF (IYEAR .EQ. 15) THEN
  YIELD = 2.333 + 0.0373*IDAY - 3.46E-04*IDAY**2
  DIGEST = 0.777 - 0.0068*IDAY + 3.95E-05*IDAY**2
ELSE
  YIELD = 2.260 + 0.1261*IDAY - 10.16E-04*IDAY**2
  DIGEST = 0.783 - 0.0032*IDAY
END IF

C****DETERMINE INITIAL MOISTURE CONTENT ON THIS DAY
C IT IS ASSUMED THAT MOISTURE CONTENT ON DAY 1 IS 550 % DB
C AND IT DECREASES BY 5 % PER DAY DURING THE SEASON.
C XMC = 550.0 - 5.0*(IDAY-1)

C****WRITE THE DETAILED RESULTS, IF REQUIRED
IF (LP .EQ. 1) WRITE (4,810) YIELD,DIGEST,XMC

810 FORMAT (/5X,'YIELD OF STANDING CROP = ',F6.3,' T/HA'/5X,
1 'DIGESTIBILITY OF STANDING CROP = ',F5.3/5X,
2 'M.C. OF STANDING CROP = ',F6.1,'% DB')
RETURN
END

C**********************************************************************
SUBROUTINE FORECAST(IDAY,R1,R2,R3,RP)
C**********************************************************************
C THIS SUBROUTINE MAKES A WEATHER FORECAST FOR 3 DAYS AND
C THEN USES IT TO DETERMINE THE REVISED PROBABILITIES OF
C EXPERIENCING DIFFERENT TYPES OF 3-DAY WEATHER.
COMMON/B5/ IYEAR,NS(25),AREA,IDAYB
COMMON/B6/ LP
COMMON/B7/ NYEARS,NREPL,IREPL
COMMON/B9/ ISEED
C
DIMENSION CUMP(8,8),PF(8,8),HP(8),RP(8)

220
DATA ((CUMP(I,J),J=1,8),I=1,8)/
1 0.343,0.535,0.611,0.692,0.832,0.879,0.972,1.000,
2 0.211,0.457,0.527,0.685,0.773,0.808,0.948,1.000,
3 0.188,0.251,0.376,0.720,0.720,0.751,0.876,1.000,
4 0.103,0.206,0.334,0.565,0.591,0.668,0.745,1.000,
5 0.109,0.127,0.145,0.181,0.472,0.527,0.872,1.000,
6 0.000,0.000,0.133,0.200,0.467,0.467,0.667,1.000,
7 0.026,0.026,0.079,0.158,0.211,0.264,0.764,1.000,
8 0.000,0.019,0.038,0.211,0.307,0.326,0.595,1.000/
DATA ((PF(K,J),J=1,8),K=1,8)/
1 0.343,0.211,0.188,0.103,0.109,0.000,0.026,0.000,
2 0.192,0.246,0.063,0.103,0.018,0.000,0.000,0.019,
3 0.076,0.070,0.125,0.128,0.018,0.133,0.053,0.019,
4 0.081,0.158,0.344,0.231,0.036,0.067,0.079,0.173,
5 0.140,0.088,0.000,0.026,0.291,0.267,0.053,0.096,
6 0.047,0.035,0.031,0.077,0.055,0.000,0.035,0.019,
7 0.093,0.140,0.125,0.077,0.345,0.200,0.500,0.269,
8 0.028,0.052,0.124,0.255,0.128,0.333,0.236,0.405/
C
C CUMP(I,J) = CUMULATIVE PROBABILITY OF MAKING JTH TYPE
C OF FORECAST FOR ITH TYPE OF KNOWN WEATHER.
C PF(K,J) = PROBABILITY OF THE KTH TYPE OF WEATHER BEING
C PREDICTED WHEN THE JTH TYPE OF WEATHER WILL
C ACTUALLY OCCUR.
C*****SET THE VALUE OF LARGE ODD INTEGER TO INITIALIZE THE RANDOM
C NUMBER GENERATOR FOR EACH REPETITION.
C IF(IDAY .EQ. NS(IYEAR)) THEN
    ISEEED = ISEEED + 3000
    NSEEED = ISEEED
ENDIF
C*****DETERMINE THE TYPE OF ACTUAL WEATHER (NW) FOR 3 DAYS
C USING RAINFALL DATA
C R1 = RAINFALL ON DAY 1
C R2 = RAINFALL ON DAY 2
C R3 = RAINFALL ON DAY 3
C IF(R1.EQ.0.0 .AND. R2.EQ.0.0 .AND. R3.EQ.0.0) THEN
    NW = 1
ELSEIF(R1.EQ.0.0 .AND. R2.EQ.0.0 .AND. R3.GT.0.0) THEN
    NW = 2
ELSEIF(R1.EQ.0.0 .AND. R2.GT.0.0 .AND. R3.EQ.0.0) THEN
    NW = 3
ELSEIF(R1.EQ.0.0 .AND. R2.GT.0.0 .AND. R3.GT.0.0) THEN
    NW = 4
ELSEIF(R1.GT.0.0 .AND. R2.EQ.0.0 .AND. R3.EQ.0.0) THEN
    NW = 5
ELSEIF(R1.GT.0.0 .AND. R2.EQ.0.0 .AND. R3.GT.0.0) THEN
    NW = 6
ELSEIF(R1.GT.0.0 .AND. R2.GT.0.0 .AND. R3.EQ.0.0) THEN
    NW = 7
ELSE
    NW = 8
ENDIF
C*****GENERATE A RANDOM NUMBER (RN) BETWEEN 0 AND 1
RN = RAN(NSEEED)
C IF(RN .LT. 0.001) GO TO 5
C*****MAKE A WEATHER FORECAST BY COMPARING THE RANDOM NUMBER
C WITH THE CUMULATIVE PROBABILITY

221
C       NF = NUMBER OF FORECAST
       N = 0
10  CONTINUE
    N = N + 1
    IF(RN .LE. CUMP(NW,N)) THEN
       NF = N
       GO TO 15
    ELSE
       GO TO 10
    ENDIF
15  CONTINUE
C*****Determine the historical probabilities of occurrence of
C different types of 3-day weather on this day
C HP(J) = historical probability of occurrence of Jth type
C of 3-day weather
    HP(1) = 0.177 + 0.00297*IDAY
    HP(2) = 0.120
    HP(3) = 0.061 + 0.000203*IDAY
    HP(4) = 0.130 - 0.000628*IDAY
    HP(5) = 0.122
    HP(6) = 0.071 - 0.000428*IDAY
    HP(7) = 0.132 - 0.000626*IDAY
    HP(8) = 0.188 - 0.00151*IDAY
C*****Use the weather forecast to revise the historical
C probabilities by applying Bayes' theorem
C RP(J) = revised probability of experiencing Jth type
C of 3-day weather on this day for a given forecast.
    K = NF
    SUM = 0.0
    DO 400 J = 1,NF
       SUM = SUM + HP(J)*PF(K,J)
400  CONTINUE
    DO 405 J = 1,NF
       RP(J) = HP(J) * PF(K,J)/SUM
405  CONTINUE
C*****Write the detailed results, if required
C IF(LP .EQ. 1) THEN
C WRITE(4,815) NW,RN,NF
815  FORMAT(/'5X,'Actual weather type = ',1L5X,
1         'Random number = ',F5.3/5X,
2         'Weather forecast type = ',1L/5X,'/weather',10X,
3         'historical',10X,'revised'/5X,'type',12X,'probability',
4         9X,'probability')
    DO 820 J = 1,NF
       WRITE(4,820) J,HP(J),RP(J)
820  FORMAT(7X,1L1,17X,F5.3,14X,F5.3)
410  CONTINUE
END
C******************************************************************************
C******************************************************************************
SUBROUTINE MANAGEMENT
C******************************************************************************
C This subroutine determines which operations are to be
C carried out at a decision time.
C COMMON/B2/ IDAY,AREA1,NF(4),LDAYC,MAN,NWT,WR(4),NM(4),NT(4),
1       IHD,RRMC,BLCM,RP(8),AR(4,200),XMC(4,200),
222
C*
C****DETERMINE WHICH OPERATIONS ARE POSSIBLE AT THIS TIME
C
IOP(1) = INDICATOR FOR ITH OPERATION, 0=NO, 1=YES
C****CHECK WHETHER CUTTING IS IN PLAN OR NOT
C
ESTIMATE THE TONNES OF HAY LYING IN SWATH (THLS)
THLS = 0.0
IF(NP(1) .EQ. 0) GO TO 5
DO 400 J = 1,NP(1)
IF(AR(1,J) .EQ. 0.0) GO TO 400
THLS = THLS + AR(1,J) * YD(1,J)
400 CONTINUE
5 CONTINUE
IF(NP(2) .EQ. 0) GO TO 10
DO 405 J = 1,NP(2)
IF(AR(2,J) .EQ. 0.0) GO TO 405
THLS = THLS + AR(2,J) * YD(2,J)
405 CONTINUE
10 CONTINUE
C
CHECK FOR STANDING AREA AND CURRENT DAY
IF(AREAL .EQ. 0.0 .OR. IDAY .GT. LDAYC) THEN
    IOP(1) = 0
    GO TO 20
ENDIF
C
CHECK FOR AREA CUT SO-FAR TO-DAY
HAYCUT = ACUT(IDAY) * YIELD
HAYCUTL = HAYCUT + WR(1) * YIELD
IF(HAYCUTL .GE. WR(3)*IHD) THEN
    IOP(1) = 0
    GO TO 20
ENDIF
C
CHECK FOR HAY LYING IN SWATH
THLS1 = THLS + WR(1) * YIELD
IF(THLS1 .LT. ISAL*WR(3)*IHD) GO TO 15
IOP(1) = 0
GO TO 20
15 CONTINUE
C
CHECK FOR THE REVISED PROBABILITY OF 3 DRY DAYS.
IF(RP(1) .GE. ARP) THEN
    IOP(1) = 1
ELSE
    IOP(1) = 0
ENDIF
20 CONTINUE
C****TRANSFER THE RAKED PLOTS INTO UNRAKED STATE IF THE TOTAL RAIN
C ON THEM IS MORE THAN OR EQUAL TO 5 MM.
IF(NP(2) .GE. 1) THEN
    CALL TRANSFER
ENDIF
C****CHECK WHETHER RAKING IS IN PLAN OR NOT
C DETERMINE THE AREA CUT AND READY FOR RAKING (AREA2)
AREA2 = 0.0
C******************************************************************************
  IF(NP(1) .EQ. 0) GO TO 25
  DO 410 J = 1,NP(1)
  IF(AR(1,J) .EQ. 0.0) GO TO 410
  IF(XMC(1,J) .GT. RKMC) GO TO 410
  AREA2 = AREA2 + AR(1,J)
410 CONTINUE
C***** IF A PLOT OF HAY IS READY FOR RAKING, THEN ALSO CONSIDER THE
C  MOIST PLOTS WHICH ARE WITHIN 10 % OF SPECIFIED RAKING M.C.
  IF(AREA2 .EQ. 0.0) GO TO 25
  AREA2 = 0.0
  DO 412 J = 1,NP(1)
  IF(AR(1,J) .EQ. 0.0) GO TO 412
  IF(XMC(1,J) .GT. RKMC+10.0) GO TO 412
  AREA2 = AREA2 + AR(1,J)
412 CONTINUE
25 CONTINUE
  IF(AREA2 .GT. 0.0) THEN
    IOP(2) = 1
  ELSE
    IOP(2) = 0
  ENDIF
C***** CHECK WHETHER BALING IS IN PLAN OR NOT
C DETERMINE RAKED AREA READY FOR BALING (AREA3)
AREA3 = 0.0
  IF(NP(2) .EQ. 0) GO TO 30
  DO 415 J = 1,NP(2)
  IF(AR(2,J) .EQ. 0.0) GO TO 415
  IF(XMC(2,J) .GT. BLMC) GO TO 415
  AREA3 = AREA3 + AR(2,J)
415 CONTINUE
  IF(AREA3 .EQ. 0.0) GO TO 30
C***** IF A PLOT OF HAY IS READY FOR BALING, THEN ALSO CONSIDER THE
C  RAKED PLOTS WHICH ARE WITHIN 5 % OF SPECIFIED BALING M.C.
  AREA3 = 0.0
  DO 417 J = 1,NP(2)
  IF(AR(2,J) .EQ. 0.0) GO TO 417
  IF(XMC(2,J) .GT. BLMC+5.0) GO TO 417
  AREA3 = AREA3 + AR(2,J)
417 CONTINUE
  IF(AREA3 .GT. 0.0) THEN
    IOP(3) = 1
  ELSE
    IOP(3) = 0
  ENDIF
C***** CHECK WHETHER CARTING IS IN PLAN OR NOT
  IF(ICART .NE. 2) THEN
    IOP(4) = 0
    GO TO 36
  ENDIF
C DETERMINE THE BALED AREA READY FOR CARTING (AREA4)
AREA4 = 0.0
  IF(NP(3) .EQ. 0) GO TO 35
  DO 420 J = 1,NP(3)
  IF(AR(3,J) .EQ. 0.0) GO TO 420
  AREA4 = AREA4 + AR(3,J)
420 CONTINUE
IF(XMC(3,J) .GT. BLMC) GO TO 420
IF(RNDW(3,J).NE.0.0 .AND. XMC(3,J).GT.BLMC-5.) GO TO 420
AREA4 = AREA4 + AR(3,J)

420 CONTINUE
35 CONTINUE
IF(AREA4 .GT. 0.0) THEN
   IOP(4) = 1
ELSE
   IOP(4) = 0
ENDIF

36 CONTINUE
C*****SET THE PRIORITY OF OPERATIONS
C  IPR(J) = PRIORITY OF JTH OPERATION
IPR(3) = 1
IPR(2) = 2
C  PD = PROBABILITY OF BEING A DRY DAY TO-DAY
C  PR = PROBABILITY OF BEING A RAINY DAY TO-DAY
PD = RP(1) + RP(2) + RP(3) + RP(4)
PR = RP(5) + RP(6) + RP(7) + RP(8)
IF(PD .GT. PR) THEN
   IPR(1) = 3
   IPR(4) = 4
ELSE
   IPR(4) = 3
   IPR(1) = 4
ENDIF

C*****CHECK FOR THE LIMITATION OF MEN AND MACHINERY AND
C DETERMINE WHICH OPERATIONS CAN ACTUALLY BE PERFORMED.
C  NMR = NUMBER OF MEN REMAINING
C  NTR = NUMBER OF TRACTORS REMAINING
NMR = MAN
NTR = NTT
I = 1

40 CONTINUE
IF(I .GT. NOP) GO TO 50
DO 430 J = 1,NOP
   IF(IPR(J) .EQ. I) GO TO 45
430 CONTINUE

45 CONTINUE
IF(IOP(J) .EQ. 0) THEN
   I = I + 1
   GO TO 40
ELSE
   IF(NMR .GE. NM(J) .AND. NTR .GE. NT(J)) THEN
      NMR = NMR - NM(J)
      NTR = NTR - NT(J)
      I = I + 1
      GO TO 40
   ELSE
      IOP(J) = 0
      I = I + 1
      GO TO 40
   ENDIF
ENDIF

50 CONTINUE
C*****WRITE THE DETAILED RESULTS, IF REQUIRED
IF(NP(1) .EQ. 0) GO TO 60
IF(LP .EQ. 1) THEN
WRITE(4,825) I HOUR, AREA1, AREA2, AREA3, THLS
825  FORMAT(//5X, 'DECISION TIME = 'I2, ' HOURS'//5X,
1 'AREA YET TO CUT = ', F6.1, ' HA'//5X,
2 'AREA READY FOR RAKING = ', F6.1, ' HA'//5X,
3 'AREA READY FOR BALING = ', F6.1, ' HA'//5X,
4 'HAY LYING IN SWATH = ', F6.1, ' TONNES')
  IF (ICART .EQ. 2) THEN
    WRITE (4,826) AREA4
826    FORMAT(//5X, 'AREA READY FOR CARTING = ', F6.1, ' HA')
ENDIF
830  FORMAT(//5X, 'OPERATIONS TO BE PERFORMED ARE:')
  IF (IOP(1) .EQ. 1) WRITE (4,831)
831     FORMAT(15X, 'CUTTING')
  IF (IOP(2) .EQ. 1) WRITE (4,832)
832     FORMAT(15X, 'RAKING')
  IF (IOP(3) .EQ. 1) WRITE (4,833)
833     FORMAT(15X, 'BALING')
  IF (IOP(4) .EQ. 1) WRITE (4,834)
834     FORMAT(15X, 'CARTING')
  IF (IOP(1) .EQ. 0 .AND. IOP(2) .EQ. 0 .AND. IOP(3) .EQ. 0 .AND.
1 IOP(4) .EQ. 0) WRITE (4,835)
835    FORMAT(15X, 'NONE')
ENDIF
60  CONTINUE
RETURN
END

C***********************************************************************
SUBROUTINE TRANSFER
C***********************************************************************
C THIS SUBROUTINE TRANSFERS THE AREA FROM RAKED PLOTS TO
C UNRAKED STATE IF THE TOTAL RAIN ON THEM IS MORE THAN OR
C EQUAL TO 5 MM.
C
COMM/B2/  IDAY, AREAL, NP(4), LDA1C, MAN, NTIT, WR(4), NM(4), NT(4),
1  IHD, RRMG, BMG, RP(8), AR(4,200), XMC(4,200),
2  YD(4,200), IOP(4), ICART, NOP, ARP, ISAL, DSTMN, DSTMX
COMM/B3/  YIELD, DIGEST, XMC, DST(4,200), CRAN(3,200),
1  RNDW(3,200), XMNUMC(3,200), TRAIN(3,200), ASTORE
COMM/B6/  LP
DIMENSION NTP(100)

C***********************************************************************
C*****FIND THE PLOTS TO BE TRANSFERRED
C NTP(I) = NO. OF ITH TRANSFERABLE PLOT
C
IP = 0
DO 400 J = 1, NP(2)
  IF (AR(2,J) .EQ. 0.0) GO TO 400
  IF (TRAIN(2,J) .LT. 5.0) GO TO 400
  IP = IP + 1
  NTP(IP) = J
400  CONTINUE
  IF (IP .EQ. 0) GO TO 5
C***********************************************************************
TRANSFER THE PLOTS FROM RAKED TO UNRAKED STATE
DO 405 I = 1, IP
  J = NTP(I)
  NP(1) = NP(1) + 1
  K = NP(1)
  AR(1,K) = AR(2,J)
226
XMC(1,K) = XMC(2,J)
YD(1,K) = YD(2,J)
DST(1,K) = DST(2,J)
XMIMC(1,K) = XMIMC(2,J)
RNW(1,K) = RNW(2,J)
CREN(1,K) = CREN(2,J)
TRUE(1,K) = TRUE(2,J)
AR(2,J) = 0.0

405 CONTINUE
C*****WRITE THE DETAILED RESULTS, IF REQUIRED
IF (LP .EQ. 1) THEN
WRITE (4,845)
845 FORMAT (/5X,'TRANSFERENCE OF WET RAKEP PLOTS TO UNRAKEP',1X,
1 'STATE'/10X,'RAKEP PLOT',10X,'UNRAKEP PLOT')
   DO 410 I = 1,IP
   M = NP(I) - IP + I
   WRITE (4,850) NTP(I),M
410 CONTINUE
ENDIF
RETURN
END

C***********************************************************************
SUBROUTINE OPERATIONS
C***********************************************************************
C THIS SUBROUTINE PERFORMS THE HAYMAKING OPERATIONS
C ACCORDING TO THE PLAN AND TRANSFERS THE HAY FROM ONE
C STATE TO ANOTHER.
COMMON/B2/ IDAY,AREAL,NP(4),LDAYC,MAN,NIT,WR(4),NM(4),NT(4),
1 IHD,REM,SMC,RP(8),AR(4,200),XMC(4,200),
2 YD(4,200),IOP(4),ICART,NOP,ARP,ISAL,DSTMN,DSTMX
C
IOP(I) = INDICATOR FOR ITH OPERATION
1 = OPERATION WILL BE PERFORMED
0 = OPERATION WILL NOT BE PERFORMED
IF (IOP (1) .EQ. 1) CALL CUTTING
IF (IOP (2) .EQ. 1) CALL RAKING
IF (IOP (3) .EQ. 1) CALL BALING
IF (IOP (4) .EQ. 1) CALL CARTING
RETURN
END

C***********************************************************************
SUBROUTINE CUTTING
C***********************************************************************
C THIS SUBROUTINE IS FOR CUTTING OPERATION
COMMON/B2/ IDAY,AREAL,NP(4),LDAYC,MAN,NIT,WR(4),NM(4),NT(4),
1 IHD,REM,SMC,RP(8),AR(4,200),XMC(4,200),
2 YD(4,200),IOP(4),ICART,NOP,ARP,ISAL,DSTMN,DSTMX
COMMON/B3/ YIELD,DIGEST,XMC,DST(4,200),CRAIN(3,200),
1 RNW(3,200),XMIMC(3,200),TRAIN(3,200),ASTORE
COMMON/B4/ IHOUR,ICOND,IBALE
COMMON/B6/ LP
COMMON/B10/ACUT(100),ARAK(100),ABAL(100),ACAR(100),TCUT(100),
1 TRAK(100),TBAL(100),TCAR(100)
COMMON/B11/ PCCL,PCRL,PCBL,PCRL,PCLL
C*****TRANSFER THE AREA FROM UNCU TO CUT STATE
AR(I,J) = AREA OF JTH PLOT IN ITH STATE OF CROP, HA
C NP(I) = NO. OF PLOTS IN ITH STATE OF CROP
C AREA1 = AREA YET TO CUT, HA
IF(AREA1 .EQ. 0.0) GO TO 5
NP(I) = NP(I) + 1
J = NP(I)
AR(1,J) = AMIN1(WR(1),AREA1)
AREA1 = AREA1 - AR(1,J)
C****ASSIGN THE INITIAL VALUES TO CUT CROP
C YD(I,J) = YIELD OF JTH PLOT IN ITH STATE OF CROP, T/HA
C DST(I,J) = DIGESTIBILITY OF JTH PLOT IN ITH STATE OF CROP, DECIMAL
C XMC(I,J) = MOISTURE CONTENT OF JTH PLOT IN ITH STATE OF CROP, % DB
C CRAIN(I,J) = CONTINUOUS RAIN ON JTH PLOT IN ITH STATE OF CROP, MM
C RNDW(I,J) = RAIN OR DEW FACTOR FOR JTH PLOT IN ITH STATE OF CROP, 0.0 OR 1.0
C XMINMC(I,J) = MINIMUM MOISTURE CONTENT OF JTH PLOT IN ITH STATE OF CROP, % DB
C TRAIN(I,J) = TOTAL RAIN AFTER CUTTING ON JTH PLOT IN ITH STATE OF CROP, MM
C CL = FRACTIONAL DRY MATTER LOSS DUE TO CUTTING
IF (ICOND .EQ. 0) THEN
   CL = 0.01
ELSE
   CL = 0.02
ENDIF
CL = CL * (1. + FCCL/100.)
YD(1,J) = YIELD * (1.0 - CL)
DST(1,J) = DIGEST * (1.0 - 1.2*CL)/(1.0 - CL)
XMC(1,J) = XMC
CRAIN(1,J) = 0.0
RNDW(1,J) = 0.0
XMINMC(1,J) = XIMC
TRAIN(1,J) = 0.0
C*****DETERMINE THE AREA CUT (ACUT) AND TIME SPENT FOR CUTTING
C (TCUT) ON THIS DAY
ACUT(IDAY) = ACUT(IDAY) + AR(1,J)
TCUT(IDAY) = TCUT(IDAY) + 1.0
C*****WRITE THE DETAILED RESULTS, IF REQUIRED
IF (LP .EQ. 1) WRITE(4,840) AR(1,J), J
840 FORMAT(/5X,'AREA CUT = ',F5.1,' HA',5X,'PLOT = ',I3)
5 CONTINUE
RETURN
END
C********************************************************************
SUBROUTINE RAKING
C********************************************************************
C THIS SUBROUTINE IS FOR RAKING OPERATION
C
C COMMON/B2/ IDAY,AREA1,NP(4),LDAYC,MAN,NIT,WR(4),NN(4),NT(4),
1 IHD,ROMC,BLCM,RP(8),AR(4,200),XMC(4,200),
2 YD(4,200),TOP(4),ICART,NOP,ARP,TSAL,DSTMIN,DSTMAX
C COMMON/B3/ YIELD,DIGEST,XMC,DST(4,200),CRAIN(3,200),
1 RNDW(3,200),XMINMC(3,200),TRAIN(3,200),ASTORE
C COMMON/B6/ LP
C COMMON/B10/ACUT(100),ARAK(100),ABAL(100),ACAR(100),TCUT(100),
1 TRAK(100),TBAL(100),TCAR(100)

228
COMMON/B11/ PCCL, PCRKL, PCBL, PCRL, PCLL
DIMENSION NRP(100)

C
C*****FIND THE PLOTS READY FOR RAKING
C NRP(I) = NO. OF ITH RAKABLE PLOT
C AREA2 = AREA READY FOR RAKING, HAc
IP = 0
AREA2 = 0.0
DO 400 J = 1,NP(1)
IF(AR(1,J) .EQ. 0.0) GO TO 400
IF(XMC(1,J) .GT. RKMC) GO TO 400
IP = IP + 1
AREA2 = AREA2 + AR(1,J)
NRP(IP) = J
400 CONTINUE
IF(IP .EQ. 0) GO TO 5
C*****IF A PLOT OF HAY IS READY FOR RAKING, THEN ALSO CONSIDER THE
C MOWN PLOTS WHICH ARE WITHIN 10 % OF SPECIFIED RAKING M.C.
IP = 0
DO 402 J = 1,NP(1)
IF(AR(1,J) .EQ. 0.0) GO TO 402
IF(XMC(1,J) .GT. RKMC+10.0) GO TO 402
IP = IP + 1
NRP(IP) = J
402 CONTINUE
C*****MERGE ALL THE RAKABLE PLOTS INTO ONE PLOT
SUM1 = 0.0
SUM2 = 0.0
SUM3 = 0.0
SUM4 = 0.0
DO 405 I = 1,IP
J = NRP(I)
SUM1 = SUM1 + AR(1,J)
SUM2 = SUM2 + YD(1,J) * AR(1,J)
SUM3 = SUM3 + DST(1,J) * AR(1,J)
SUM4 = SUM4 + TRAIN(1,J) * AR(1,J)
AR(1,J) = 0.0
405 CONTINUE
J = NRP(1)
AR(1,J) = SUM1
YD(1,J) = SUM2/SUM1
DST(1,J) = SUM3/SUM1
TRAIN(1,J) = SUM4/SUM1
C SET THE M.C. OF MERGED PLOT
C XMCMP = M.C. OF MERGED PLOT
XMCMP = XMC(1,J)
DO 407 I = 1,IP
J = NRP(I)
IF(XMC(1,J) .GE. XMCMP) GO TO 407
XMCMP = XMC(1,J)
407 CONTINUE
J = NRP(1)
XMC(1,J) = XMCMP
XMINMC(1,J) = XMC(1,J)
RNDW(1,J) = 0.0
TRAIN(1,J) = 0.0
C*****TRANSFER THE AREA FROM UNRAKED TO RAKED STATE
NP(2) = NP(2) + 1

229
K = NP(2)
AR(2,K) = AMin1(WR(2),AR(1,J))
AR(1,J) = AR(1,J) - AR(2,K)

C*****Determine the raking losses and update the yield and
C digestibility of hay
C
RKL = fractional dry matter losses due to raking
RKL = (1.0 + PCRKL/100.) * 0.267 * XM(1,J)**0.745
1 + 0.002*TRAIN(1,J)
YD(2,K) = YD(1,J) * (1.0 - RKL)
DST(K,2) = DST(1,J) * (1.0 - 1.2*RKL)/(1.0 - RKL)
If(YD(2,K),LT,0.0) YD(2,K) = 0.0
If(DST(2,K),LT,0.0) DST(2,K) = 0.0

C*****Assign the other values to raked plot
XM(2,K) = XM(1,J)
CRA(2,K) = 0.0
RND(2,K) = 0.0
XMINMC(2,K) = XM(2,K)
TRAIN(2,K) = 0.0

C*****Determine the area raked (ARAK) and time spent for raking
C
(Trak) on this day
ARAK(IDAY) = ARAK(IDAY) + AR(2,K)
TRAK(IDAY) = TRAK(IDAY) + 1.0

C*****Write the detailed results, if required
IF(LP,EQ,1) THEN
WRITE(4,845)
845 FORMAT(1/5X,'Plots ready for raking are: ')
DO 410 I = 1,IP
WRITE(4,850) NRP(I)
850 FORMAT(15X,I3)
410 CONTINUE
WRITE(4,855) NRP(I),AR(2,K),K
855 FORMAT(5X,'Merged plot no. = ',I3/5X,'Area raked = ',
1 'F6.1,' 'Ha','F5X,'Plot no. = ',I3)
ENDIF
5 CONTINUE
RETURN
END

C***************************************************************************
SUBROUTINE BALKING
C***************************************************************************
C
THIS SUBROUTINE IS FOR BALING OPERATION
C
COMMON/B2/ IDAY,AREA1,NP(4),LDAYC,MAN,NIT,WR(4),NM(4),NT(4),
1 IHD,RMC,BMC,RP(8),AR(4,200),XM(4,200),
2 YD(4,200),IOP(4),ICART,NOP,ARP,ISAL,DSTMN,DSTMAX
COMMON/B3/ YIELD,DIGEST,XMC,DST(4,200),CRAIN(3,200),
1 RNDN(3,200),XMIMC(3,200),TRAIN(3,200),ASTORE
COMMON/B6/ LP
COMMON/B10/ACUT(100),ARAK(100),ABAL(100),ACAR(100),TCUT(100),
1 TRAK(100),TBAL(100),TCAR(100)
COMMON/B11/ PCCL,PCRKL,PCBL,PCRL,PCLL
DIMENSION NBP(100)
C
C*****Find the plots ready for baling
C
NBP(I) = No. of Ith balable plot
IP = 0
DO 400 J = 1,NP(2)
IF(AR(2,J),EQ,0.0) GO TO 400

230
IF(XMC(2,J) .GT. BLMC) GO TO 400
IP = IP + 1
NBP(IP) = J
400 CONTINUE
IF(IP .EQ. 0) GO TO 5
C*****IF A PLOT OF HAY IS READY FOR BALING, THEN ALSO CONSIDER THE
C RAKED PLOTS WHICH ARE WITHIN 5 % OF SPECIFIED BALING M.C.
IP = 0
DO 402 J = 1,NP(2)
IF(AR(2,J) .EQ. 0.0) GO TO 402
IF(XMC(2,J) .GT. BLMC+5.0) GO TO 402
IP = IP + 1
NBP(IP) = J
402 CONTINUE
C*****MERGE ALL THE BALABE PLOTS INTO ONE PLOT
SUM1 = 0.0
SUM2 = 0.0
SUM3 = 0.0
SUM4 = 0.0
DO 405 I = 1,IP
J = NBP(I)
SUM1 = SUM1 + AR(2,J)
SUM2 = SUM2 + YD(2,J) * AR(2,J)
SUM3 = SUM3 + DST(2,J) * AR(2,J)
SUM4 = SUM4 + TRAIN(2,J) * AR(2,J)
AR(2,J) = 0.0
405 CONTINUE
J = NBP(1)
AR(2,J) = SUM1
YD(2,J) = SUM2/SUM1
DST(2,J) = SUM3/SUM1
TRAIN(2,J) = SUM4/SUM1
C SET THE M.C. OF MERGED PLOT
C XMCM = M.C. OF MERGED PLOT
XMCM = XMC(2,J)
DO 407 I = 1,IP
J = NBP(I)
IF(XMC(2,J) .GE. XMCM) GO TO 407
XMCM = XMC(2,J)
407 CONTINUE
J = NBP(1)
XMC(2,J) = XMCM
XMINMC(2,J) = XMC(2,J)
RNDW(2,J) = 0.0
CRAIN(2,J) = 0.0
C*****TRANSFER THE AREA FROM RAKED TO BALED STATE
NP(3) = NP(3) + 1
K = NP(3)
C DETERMINE THE WORK RATE OF BALING OPERATION IN HA/HR
XWR = WR(3)/YD(2,J)
AR(3,K) = AMIN1(XWR,AR(2,J))
AR(2,J) = AR(2,J) - AR(3,K)
C*****DETERMINE THE BALING LOSSES AND UPDATE THE YIELD AND
C DIGESTIBILITY OF HAY
C BLL = FRACTIONAL DRY MATTER LOSSES DUE TO BALING
BLL = (1. + PCBL/100.) * 0.267 * XMC(2,J)**-0.745
1 + 0.002*TRAIN(2,J)
YD(3,K) = YD(2,J) * (1.0 - BLL)
DST(3,K) = DST(2,J) * (1.0 - 1.2*BLR)/(1.0 - BLR)
IF(YD(3,K) .LT. 0.0) YD(3,K) = 0.0
IF(DST(3,K) .LT. 0.0) DST(3,K) = 0.0
C*****ASSIGN THE OTHER VALUES TO BALED PLOT
XMC(3,K) = XMC(2,J)
CRAIN(3,K) = 0.0
RNDE(3,K) = 0.0
TRAIN(3,K) = 0.0
XMIMC(3,K) = XMNC(3,K)
C*****DETERMINE THE AREA BALED (ABAL) AND TIME SPENT FOR BALING
C (TBAL) ON THIS DAY
ABAL(IDAY) = ABAL(IDAY) + AR(3,K)
TBAL(IDAY) = TBAL(IDAY) + 1.0
C*****WRITE THE DETAILED RESULTS, IF REQUIRED
IF(LP .EQ. 1) THEN
WRITE(4,845)
845 FORMAT(/5X,'PLOTS READY FOR BALING ARE:')
DO 410 I = 1,LP
WRITE(4,850) NBP(I)
410 CONTINUE
WRITE(4,855) NBP(I),AR(3,K),K
855 FORMAT(5X,'MERGED PLOT NO. =',I3/5X,'AREA BALED =',
1 F6.1,' HA',5X,'PLOT =',I3)
ENDIF
C*****UPDATE THE AREA IN STORE (FOR ICART =0 & 1)
IF(ICART .NE. 2) ASTORE = ASTORE + AR(3,K)
5 CONTINUE
RETURN
END

SUBROUTINE CARTING
C**************************************************************
C**************************************************************
C THIS SUBROUTINE IS FOR CARTING OPERATION
C
COMMON/B2/ IDAY,AREA1,AR(4),LDAYC,MAN,NIT,WR(4),NM(4),NT(4),
1 IHD,RMC,BLC,RP(8),AR(4,200),XMC(4,200),
2 YD(4,200),IOP(4),ICART,NOP,ARP,ISAL,DSTMN,DSTMX
COMMON/B3/ YIELD,DIGEST,XMC,DST(4,200),CRAIN(3,200),
1 RNDE(3,200),XMIMC(3,200),TRAIN(3,200),ASTORE
COMMON/B6/ LP
COMMON/B10/CUT(100),ARAK(100),BAL(100),ACAR(100),TCUT(100),
1 TRAK(100),TBAL(100),TCAR(100)
1 DIMENSION NCP(100)
C
C*****FIND THE PLOTS READY FOR CARTING
C
NCP(I) = NO. OF ITH CARTABLE PLOT
IP = 0
DO 400 J = 1,NP(3)
IF(AR(3,J) .EQ. 0.0) GO TO 400
IF(XMC(3,J) .GT. BLMC) GO TO 400
IF(RNDE(3,J) .GE. 0.0 .AND. XMNC(3,J) .GT. BLMC-5.) GO TO 400
IP = IP + 1
NCP(IP) = J
400 CONTINUE
IF(IP .EQ. 0) GO TO 5

C*****MERGE ALL THE CARTABLE PLOTS INTO ONE PLOT
SUM1 = 0.0
SUM2 = 0.0
SUM3 = 0.0
SUM4 = 0.0
SUM5 = 0.0
DO 405 I = 1,IP
J = NCP(I)
SUM1 = SUM1 + AR(3,J)
SUM2 = SUM2 + XMC(3,J) * AR(3,J)
SUM3 = SUM3 + YD(3,J) * AR(3,J)
SUM4 = SUM4 + DST(3,J) * AR(3,J)
SUM5 = SUM5 + TRAIN(3,J) * AR(3,J)
AR(3,J) = 0.0
405 CONTINUE
J = NCP(1)
AR(3,J) = SUM1
XMC(3,J) = SUM2/SUM1
YD(3,J) = SUM3/SUM1
DST(3,J) = SUM4/SUM1
TRAIN(3,J) = SUM5/SUM1
XMINMC(3,J) = XMC(3,J)
RNDW(3,J) = 0.0
CRAIN(3,J) = 0.0
C*****TRANSFER THE BALED HAY FROM FIELD TO STORE
NP(4) = NP(4) + 1
K = NP(4)
C DETERMINE THE WORK RATE OF CARTING OPERATION IN HA/HR
XWR = WR(4)/YD(3,J)
AR(4,K) = AMIN1(XWR,AR(3,J))
AR(3,J) = AR(3,J) - AR(4,K)
C*****ASSIGN THE OTHER VALUES TO STORED HAY
YD(4,K) = YD(3,J)
DST(4,K) = DST(3,J)
XMC(4,K) = XMC(3,J)
C*****UPDATE THE AREA IN STORE
ASTORE = ASTORE + AR(4,K)
C*****UPDATE THE AREA CARTED (ACAR) AND TIME SPENT FOR CARTING
C (TCAR) ON THIS DAY
ACAR(IDAY) = ACAR(IDAY) + AR(4,K)
TCAR(IDAY) = TCAR(IDAY) + 1.0
C*****WRITE THE DETAILED RESULTS, IF REQUIRED
IF(LP .EQ. 1) THEN
WRITE(4,845)
845 FORMAT(//'PLOTS READY FOR CARTING ARE: //'")
DO 410 I = 1,IP
WRITE(4,850) NCP(I)
850 FORMAT(15X,I3)
410 CONTINUE
WRITE(4,855) NCP(1),AR(4,K),K
855 FORMAT(5X,'MERGED PLOT NO. = ',I3/5X,'AREA CARTED = ',
1 F6.1,' HA',5X,'PLOT = ',I3)
ENDIF
END
C*****************************************************************************
SUBROUTINE STATUSOUR
C*****************************************************************************
C THIS SUBROUTINE UPDATES THE STATUS OF HAYMAKING DURING
EACH HOUR OF THE DAY. FOLLOWING VARIABLES ARE UPDATED:

1. MOISTURE CONTENT
2. YIELD
3. DIGESTIBILITY

COMMON/B1/ NDAYS, IWTYPE, DATE (100), RAIN (100), VPDN (100),
   1   RN (100), TN (100), VPD (100, 20), W (100, 20),
   2   RG (100, 20), R (100, 20), T (100, 20)
COMMON/B2/ IDAY, AREA1, NP (4), LDAYC, MAN, NTT, WR (4), NM (4), NT (4),
   1   IHDC, RMC, BLM, RP (8), AR (4, 200), XMÇ (4, 200),
   2   YD (4, 200), IOP (4), ICART, NOP, ARP, ISAL, DSIMIN, DSIMAX
COMMON/B3/ YIELD, DIGEST, XMC, DST (4, 200), CRAIN (3, 200),
   1   RNDW (3, 200), XMNNC (3, 200), TRAIN (3, 200), ASTORE
COMMON/B4/ IHR, ICOND, IBALE
COMMON/B6/ LP
CHARACTER DATE*6

IST = STATE OF CROP, 1=UNRAKED, 2=RAKED, 3=BALED

DO 405 I = 1, NOP-1
   IST = I
   IF (NP (I) .EQ. 0) GO TO 405
   DO 400 J = 1, NP (I)
   IF (AR (I, J) .EQ. 0.0) GO TO 400

XMBH = MOISTURE CONTENT AT THE BEGINNING OF HOUR, % DB
XMBH = XMC (I, J)
   IF (R (IDAY, IHR) .GT. 0.0) THEN
      CALL RAINYHOUR (IST, ICOND, IBALE, IDAY, IHR, CRAIN (I, J), CM)
      TRAIN (I, J) = TRAIN (I, J) + R (IDAY, IHR)
   ELSE
      CALL DRYHOUR (IST, ICOND, IBALE, IDAY, IHR, RNDW (I, J),
         XMNN, CM)
   ENDIF
   XMC (I, J) = XMBH + CM
   XMC (I, J) = AMIN1 (XMC (I, J), 700.0)
   XMC (I, J) = AMAX1 (XMC (I, J), 14.0)

C*****DETERMINE LOSSES DUE TO ENVIRONMENTAL FACTORS AND UPDATE
C
YIELD AND DIGESTIBILITY

C
XMC = AVERAGE M.C. FOR THIS HOUR, % DB
C
XLL = FRACTIONAL DRY MATTER LOSSES DUE TO LEACHING
C
RL = FRACTIONAL DRY MATTER LOSSES DUE TO RESPIRATION

C
AMC = (XMC (I, J) + XMBH)/2.0
   IF (R (IDAY, IHR) .GT. 0.0) THEN
      CALL LEACHING (IST, ICOND, R (IDAY, IHR), XMNNC (I, J), XLL)
   ELSE
      XLL = 0.0
   ENDIF

C
SET THE TEMP. OF HAY
IF (IST .EQ. 3) THEN
   TEMP = T (IDAY, IHR) + 5.0
ELSE
   TEMP = T (IDAY, IHR) + 3.0
ENDIF
CALL RESPIRATION (AMC, TEMP, RL)
TL = XLL + RL
YD (I, J) = YD (I, J) * (1.0 - TL)
DST (I, J) = (DST (I, J) - TL)/(1.0 - TL)
   IF (YD (I, J) .LT. 0.0) YD (I, J) = 0.0
   IF (DST (I, J) .LT. 0.0) DST (I, J) = 0.0

234
C****UPDATE MINIMUM MOISTURE CONTENT AND SET THE VALUE OF RNDW
IF (XMC(I,J) .LE. XMINMC(I,J)) THEN
    XMINMC(I,J) = XMC(I,J)
    RNDW(I,J) = 0.0
ELSE
    RNDW(I,J) = 1.0
ENDIF
400 CONTINUE
405 CONTINUE
C*****WRITE THE DETAILED RESULTS, IF REQUIRED
IF (LP .EQ. 1 .AND. NP(I) .GE. 1) THEN
WRITE(4,860) I, HOUR, AREA1, ANSTORE
860 FORMAT(/15X,'STATUS AT THE END OF HOUR ',I2,5X,
1 'AREA YET TO CUT = ',F6.1,' HA',5X,'AREA IN STORE = ',
2 F6.1,' HA'/2X,'CROP',4X,'PLOT',3X,'AREA',3X,'M.C.',3X,
3 'YIELD',3X,'DIGEST',3X,'CRAIN',3X,'RNDW',3X,'MINMC',3X,
4 'TRAIN'/2X,'STATE',3X,'NO.'/
     DO 415 I = 1, NAP-1
     IF (NP(I) .EQ. 0) GO TO 415
     DO 410 J = 1, NP(I)
     IF (AR(I,J) .EQ. 0.0) GO TO 410
     IF (I .EQ. NOP) THEN
        WRITE(4,865) I, J, AR(I,J), XMC(I,J), YD(I,J), DST(I,J)
     ELSE
        WRITE(4,867) I, J, AR(I,J), XMC(I,J), YD(I,J),
1       DST(I,J), CRAIN(I,J), RNDW(I,J), XMINMC(I,J), TRAIN(I,J)
     ENDIF
410 CONTINUE
415 CONTINUE
ENDIF
RETURN
END
C********************************************************************
SUBROUTINE RAINYHOUR(I, ICND, IBALE, IDAY, IHOUR, CRAIN, CM)
C********************************************************************
C THIS SUBROUTINE DETERMINES THE CHANGE (INCREASE) IN
C MOISTURE CONTENT DURING A RAINY HOUR.
COMMON/B1/ NDAY, MTYPE, DATE, RAIN(100), VPDN(100),
1        RN(100), TN(100), VPD(100,20), W(100,20),
2        RG(100,20), R(100,20), T(100,20)
CHARACTER*6
C CM = CHANGE IN MOISTURE CONTENT DUE TO RAIN, % DB
CRAIN1 = CRAIN
CRAIN2 = CRAIN + R(IDC, IHOUR)
IF (IST .EQ. 3) GO TO 5
C****DTERMINE CHANGE IN M.C. OF SWATH HAY
IF (CRAIN1 .EQ. 0.0) THEN
    CM1 = 0.0
ELSEIF (CRAIN1 .LT. 0.5) THEN
    CM1 = CRAIN1/0.5 * 131.8*0.5**0.29*(1+ICOND)**0.27
ELSE
    CM1 = 131.8*CRAIN1**0.29*(1+ICOND)**0.27
ENDIF
IF (CRAIN2 .LT. 0.5) THEN
    CM2 = CRAIN2/0.5 * 131.8*0.5**0.29*(1+ICOND)**0.27
ELSE
235
\[ CM2 = 131.8 \times CRAIN2^{0.29} \times (1 + ICOND)^{0.27} \]

ENDIF
CM = CM2 - CM1
GO TO 10

5 CONTINUE

C*****Determine change in M.C. of baled hay
IF (IBALE .EQ. 1) CM = 2.0 \times R(IDAY, IHOUR)
IF (IBALE .EQ. 2) CM = 0.57 \times R(IDAY, IHOUR)

10 CONTINUE

C*****Set the value of CRAIN
IF (IHOUR .EQ. 20) THEN
    IF (RN(IDAY) .EQ. 0.0) THEN
        CRAIN = 0.0
    ELSE
        CRAIN = CRAIN2
    ENDIF
ELSE
    IF (R(IDAY, IHOUR+1) .EQ. 0.0) THEN
        CRAIN = 0.0
    ELSE
        CRAIN = CRAIN2
    ENDIF
ENDIF
RETURN
END

C*******************************************************************************
SUBROUTINE DRYHOUR(IST, ICOND, IBALE, IDAY, IHOUR, RNW, XMBH, CM)
*******************************************************************************
C
C This subroutine determines the change in moisture content
C during a rain-free hour.
COMMON/B1/ NDAYS, IWTYPE, DATE(100), RAIN(100), VPDN(100),
1 \begin{align*}
& RN(100), TN(100), VPD(100, 20), W(100, 20), \\
& 2 \begin{align*}
& RG(100, 20), R(100, 20), T(100, 20)
\end{align*}
\end{align*}
CHARACTER DATE*6
IF (IST .EQ. 3) GO TO 5
C*****Determine change in M.C. of swath hay
C SET THE VALUE OF RAKING FACTOR (RK)
IF (IST .EQ. 2) THEN
    RK = 1.0
ELSE
    RK = 0.0
ENDIF

C CHECK THE WEATHER TYPE AND RAIN/DEW WATER AND THEN
C CALCULATE THE CHANGE IN M.C. FOR THIS HOUR (CM)
IF (IWTYPE .EQ. 1) GO TO 1
IF (IWTYPE .EQ. 2) GO TO 2
IF (IWTYPE .EQ. 3) GO TO 3

1 CONTINUE
C USE VAPOUR PRESSURE DEFICIT DATA TO CALCULATE CM
IF (RNW .EQ. 0.0) THEN
    CM = -0.0069 \times XMBH^{1.50} \times VPD(IDAY, IHOUR)^{0.46}
    \begin{align*}
    & \times (1 + ICOND)^{0.43} \times (1 + RK)^{0.82}
    \end{align*}
ELSE
    CM = -0.0529 \times XMBH^{1.14} \times VPD(IDAY, IHOUR)^{0.27}
    \begin{align*}
    & \times (1 + ICOND)^{0.28}
    \end{align*}
ENDIF
GO TO 10

2 CONTINUE
USE VAPOUR PRESSURE DEFICIT AND RADIATION DATA TO
CALCULATE CM
IF (RNDW .EQ. 0.0) THEN
   CM = -0.0031 * XMHB**1.58 * VPD(IDAY, IHour)**0.33
   1 * RG(IDAY, IHour)**0.50 * (1+ICOND)**0.45
   2 * (1+RK)**0.93
ELSE
   CM = -0.0767 * XMHB**1.02 * RG(IDAY, IHour)**0.38
   1 * (1+ICOND)**0.22
ENDIF
GO TO 10
3 CONTINUE

USE VAPOUR PRESSURE DEFICIT, RADIATION AND WIND SPEED
DATA TO CALCULATE CM
IF (RNDW .EQ. 0.0) THEN
   CM = -0.0027 * XMHB**1.56 * VPD(IDAY, IHour)**0.29
   1 * RG(IDAY, IHour)**0.56 * W(IDAY, IHour)**0.14
   2 * (1+ICOND)**0.44 * (1+RK)**0.91
ELSE
   CM = -0.0767 * XMHB**1.02 * RG(IDAY, IHour)**0.38
   1 * (1+ICOND)**0.22
ENDIF
GO TO 10
5 CONTINUE

DETERMINE CHANGE IN M.C. OF BALED HAY
CM = -0.023 * XMHB**0.87 * VPD(IDAY, IHour)**0.31
10 CONTINUE
RETURN
END

SUBROUTINE LEACHING (IST, ICOND, RAIN, XMCR, XLL)

THIS SUBROUTINE DETERMINES THE LEACHING LOSSES DUE TO RAIN
COMMON/B1L/ PCCL, PCRKL, PCBL, PCRL, PCLL

VARIABLES USED ARE:
RAIN = AMOUNT OF RAINFALL, MM
XLL = FRACTIONAL DRY MATTER LOSS DUE TO LEACHING
XMCR = M.C. OF HAY AT THE START OF RAIN, % DB
IF (IST .EQ. 3) THEN
   XLL = 0.0
GO TO 5
ENDIF
IF (ICOND .EQ. 0) THEN
   XLL = 0.00563 * RAIN * EXP(-0.0066*XMCR)
ELSE
   XLL = 0.00598 * RAIN * EXP(-0.0049*XMCR)
ENDIF
XLL = XLL * (1. + PCLL/100.)
5 CONTINUE
RETURN
END

SUBROUTINE RESPIRATION (AMC, TEMP, RL)

THIS SUBROUTINE DETERMINES THE RESPIRATION LOSSES DURING
FIELD DRYING OF HAY.
COMMON/B1L/ PCCL, PCRKL, PCBL, PCRL, PCLL

237
VARIABLES USED ARE:
AMC = AVERAGE MOISTURE CONTENT, % DB
TEMP = TEMPERATURE, DEG. C
RL = FRACTIONAL DRY MATTER LOSS DUE TO RESPIRATION

IF(AMC .GE. 25.0) THEN
   RL = 1.17E-06 * AMC * EXP(0.066*TEMP)
ELSE
   RL = 0.0
ENDIF
RL = RL * (1. + PCRL/100.)
RETURN
END

******************************************************************************
SUBROUTINE STATUSNIGHT
******************************************************************************

THIS SUBROUTINE UPDATES THE STATUS OF HAYMAKING DURING NIGHT TIME. FOLLOWING VARIABLES ARE UPDATED:
1. MOISTURE CONTENT
2. YIELD
3. DIGESTIBILITY

COMMON/B1/ NDAYS, INTYPE, DATE(100), RAIN(100), VPDN(100),
    1 RN(100), TN(100), VPD(100,20), W(T(100,20),
    2 RG(100,20), R(100,20), T(100,20)
COMMON/B2/ IDAY, AREA1, NP(4), LDAYC, MAN, NT, WR(4), NM(4), NT(4),
    1 IHSD, RMC, BLMC, RP8, AR(4,200), XMC(4,200),
    2 YD(4,200), IOP(4), ICART, NOP, ARP, ISAL, DDMIN, DSMAX
COMMON/B3/ YIELD, DIGEST, XMCM, DST(4,200), CPA(3,200),
    1 RNDW(3,200), XMINT(3,200), TRAIN(3,200), ASTORE
COMMON/B4/ IHR, ICND, IBALE
COMMON/B6/ LP

CHARACTER DATE*6

C
IST = STATE OF CROP, 1=UNRAIRED, 2=RAINED, 3=BALED

DO 405 I = 1, NOP-1
IST = I
IF(NP(I) .EQ. 0) GO TO 405
DO 400 J = 1, NP(I)
IF(R(I,J) .EQ. 0) GO TO 400

C
XM = MOISTURE CONTENT AT THE END OF DAY, % DB
XM = XM(C(I,J)

IF(RN(IDAY) .GT. 0.0) THEN
   CALL RAINNIGHT(IST, ICND, IBALE, IDAY, CPA(I,J), MN)
   TRAIN(I,J) = TRAIN(I,J) + RN(IDAY)
ELSE
   CALL DRYNIGHT(IST, IDAY, XM, YD(I,J), MN)
ENDIF

XM(C(I,J)) = XM + MN
XM(C(I,J)) = A Min1(XM(C(I,J), 700.0))
XM(I,J) = A Max1(XM(I,J), 14.0)

DETERMINE THE LOSSES DUE TO ENVIRONMENTAL FACTORS AND
UPDATE THE YIELD AND DIGESTIBILITY OF HAY.

C
AMC = AVERAGE MOISTURE CONTENT DURING THE NIGHT, % DB
XLIN = FRACTIONAL DRY MATTER LOSS DUE TO LEACHING DURING
    THE NIGHT.
C
AR = AVERAGE FRACTIONAL DRY MATTER LOSS DUE TO RESPIRATION DURING
    NIGHT.

AMC = (XM(C(I,J) + XM) / 2.0

238
IF(RN(IDAY) .GT. 0.0) THEN
   CALL LEACHING(IST,ICOND,RN(IDAY),XMINMC(I,J),XLIN)
ELSE
   XLIN = 0.0
ENDIF

C SET THE TEMP. OF HAY
IF(IST .EQ. 3) THEN
   TEMP = TN(IDAY) + 5.0
ELSE
   TEMP = TN(IDAY)
ENDIF

CALL RESPIRATION(AMC,TEMP,ARLN)
TN = XLIN + 10.0 * ARLN
YD(I,J) = YD(I,J) * (1.0 - TN)
DST(I,J) = (DST(I,J) - TN)/(1.0 - TN)
IF(YD(I,J) .LT. 0.0) YD(I,J) = 0.0
IF(DST(I,J) .LT. 0.0) DST(I,J) = 0.0

C*****UPDATE MINIMUM M.C. AND SET THE VALUE OF RNDW
IF(XMC(I,J) .LE. XMINMC(I,J)) THEN
   XMINMC(I,J) = XMC(I,J)
   RNDW(I,J) = 1.0
ELSE
   RNDW(I,J) = 1.0
ENDIF

400 CONTINUE
405 CONTINUE

C*****WRITE THE DETAILED RESULTS, IF REQUIRED
IF(LP .EQ. 1 .AND. NP(1) .GE. 1) THEN
WRITE(4,860) RN(IDAY),VPDN(IDAY),TN(IDAY),AREA1,ASTORE
860 FORMAT(/5X,'STATUS AT THE END OF THIS NIGHT',/5X,
1 'RAIN = ',F6.2,3X,'VPDN = ',F5.3,3X,'TEMP = ',F5.2/5X,
2 'AREA YET TO CUT = ',F6.1,' HA',5X,'AREA IN STORE = ',
3 'F6.1,' HA'//2X,'CROP',4X,'PLOT',3X,'AREA',3X,'M.C.',3X,
4 'YIELD',3X,'DIGEST',3X,'CRAIN',3X,'RNDW',3X,'MINMC',3X,
5 'RAIN'/2X,'STATE',3X,'NO.'/
DO 415 I = 1,NOP-1
IF(NP(I) .EQ. 0) GO TO 415
DO 410 J = 1,NP(I)
IF(AR(I,J) .EQ. 0.0) GO TO 410
IF(I .EQ. NOP) THEN
   WRITE(4,865) I,J,AR(I,J),XMC(I,J),YD(I,J),DST(I,J)
ELSE
   WRITE(4,867) I,J,AR(I,J),XMC(I,J),YD(I,J),
1   DST(I,J),CRAIN(I,J),RNDW(I,J),XMINMC(I,J),TRAIN(I,J)
ENDIF
865 FORMAT(3X,1L,7X,13,F7.1,F7.1,F8.4,F9.4)
867 FORMAT(3X,1L,7X,13,F7.1,F7.1,F8.4,F9.4,F8.2,F7.1,2F8.1)
410 CONTINUE
415 CONTINUE
ENDIF
END

C********************************************************************
SUBROUTINE RAINYDAY(IST,ICOND,IBALE,IDAY,CRAIN,CMN)
C********************************************************************
C THIS SUBROUTINE DETERMINES THE CHANGE (INCREASE) IN
C MOISTURE CONTENT DURING A RAINY NIGHT
C
239
C
CMN = CHANGE IN MOISTURE CONTENT DUE TO RAIN DURING THE NIGHT, % DB
CRAIN1 = CRAIN
CRAIN2 = CRAIN + RN(IDAY)
IF(IST .EQ. 3) GO TO 5
C*****Determine change in M.C. of swath hay
IF(CRAIN1 .EQ. 0.0) THEN
    CMN1 = 0.0
ELSEIF(CRAIN1 .LT. 0.5) THEN
    CMN1 = CRAIN1/0.5 * 131.8*0.5**0.29*(1+ICOND)**0.27
ELSE
    CMN1 = 131.8*CRAIN1**0.29*(1+ICOND)**0.27
ENDIF
IF(CRAIN2 .LT. 0.5) THEN
    CMN2 = CRAIN2/0.5 * 131.8*0.5**0.29*(1+ICOND)**0.27
ELSE
    CMN2 = 131.8 * CRAIN2**0.29 * (1+ICOND)**0.27
ENDIF
CMN = CMN2 - CMN1
GO TO 10
5 CONTINUE
C*****Determine change in M.C. of baled hay
IF(IBALE .EQ. 1) CMN = 2.0 * RN(IDAY)
10 CONTINUE
C*****Set the value of CRAIN
IF(R(IDAY+1,7) .EQ. 0.0) THEN
    CRAIN = 0.0
ELSE
    CRAIN = CRAIN2
ENDIF
RETURN
END

SUBROUTINE DRYNIGHT(IST,IDAY,XME,YD,CMN)

C THIS SUBROUTINE DETERMINES THE CHANGE IN MOISTURE CONTENT DURING A RAIN-FREE NIGHT.
COMMON/B1/ NDAYS, IWTYPE, DATE(100), RAIN(100), VPDN(100),
1        RN(100), TN(100), VPD(100,20), W(100,20),
2        RG(100,20), R(100,20), T(100,20)
C CMN = CHANGE IN MOISTURE CONTENT DURING NIGHT, % DB
C XME = MOISTURE CONTENT AT THE END OF THIS DAY, % DB
C YD = YIELD OF PASTURE, % DB
IF(IST .EQ. 3) THEN
    CMN = 0.0
ELSE
    CMN = 107.8 - 0.14*XME - 83.58*VPDN(IDAY) - 8.47*YD
    IF(CMN .LT. -8.0) CMN = -8.0
ENDIF
RETURN
END

SUBROUTINE ENDRYR
C THIS SUBROUTINE STORES THE SUMMARY RESULTS FOR EACH YEAR
AND EACH REPLICA.
COMMON/B1/ NDAYS, IWTYPE, DATE(100), RAIN(100), VPDN(100),
1 RN(100), TN(100), VPD(100,20), W(100,20),
2 RG(100,20), R(100,20), T(100,20)
COMMON/B2/ IDAY, AREA1, NP(4), LDAYC, MAN, NIT, WR(4), NM(4), NT(4),
1 IHID, RRMC, BLMC, RP(8), AR(4,200), XMC(4,200),
2 YD(4,200), IOP(4), ICART, NOP, ARP, ISAL, DSTMIN, DSTMAX
COMMON/B3/ YIELD, DIGEST, XMNC, DST(4,200), CRAIN(3,200),
1 RNDW(3,200), XMIMC(3,200), TRAIN(3,200), ASTORE
COMMON/B4/ IHOURL, ICOND, IBALE
COMMON/B5/ IYEAR, NS(25), AREA, IDAYB
COMMON/B6/ LP
COMMON/B7/ NYEARS, NREPL, IREPL
COMMON/B8/ AST(25,10), AUF(25,10), AUCT(25,10),
1 ASWATH(25,10), ABALED(25,10), DM(25,10),
2 DDM(25,10), IHDAYS(25,10)
COMMON/B9/ ACUT(100), ARAK(100), ABAL(100), ACAR(100), TCUT(100),
1 TRAK(100), TBAL(100), TCAR(100)

CHARACTER DATE*6

C
M = IYEAR
N = IREPL
C*****DETERMINE AREA IN STORE (AST)
AST(M,N) = ASTORE
C*****DETERMINE UNFINISHED AREA (AUF)
AUF(M,N) = AREA - ASTORE
C*****DETERMINE UNCUT AREA (AUCT)
AUCT(M,N) = AREA1
C*****DETERMINE AREA LYING IN SWATH (ASWATH)
SUM = 0.0
DO 405 I = 1, 2
  DO 400 J = 1, NP(I)
  SUM = SUM + AR(I,J)
400 CONTINUE
405 CONTINUE
ASWATH(M,N) = SUM
C*****DETERMINE BALED AREA LYING IN FIELD (ABALED)
SUM = 0.0
DO 410 J = 1, NP(3)
  SUM = SUM + AR(3,J)
410 CONTINUE
ABALED(M,N) = SUM
IF(ICART .EQ. 1) ABALED(M,N) = 0.0
C*****DETERMINE TOTAL DRY MATTER (DM) AND TOTAL DIGESTIBLE
C DRY MATTER (DDM) OF STORED HAY.
SUM1 = 0.0
SUM2 = 0.0
DO 415 J = 1, NP(NOP)
  SUM1 = SUM1 + AR(NOP,J) * YD(NOP,J)
  SUM2 = SUM2 + AR(NOP,J) * YD(NOP,J) * DST(NOP,J)
415 CONTINUE
DM(M,N) = SUM1
DM(M,N) = SUM2
C*****DETERMINE NUMBER OF DAYS REQUIRED TO COMPLETE THE
C HAYMAKING OPERATIONS (IHDCAS)
IHDCAS(M,N) = IDAY - IDAYB + 1
C*****WRITE THE SUMMARY RESULTS FOR EACH DAY DURING THE SEASON,
C       IF REQUIRED.
IF( LP .EQ. 2) THEN
WRITE(5,324) M,N,AST(M,N),IHDAYS(M,N)
324   FORMAT(1',10X,'YEAR = ',I2,5X,'REPLICATION = ',I2/5X,
1   'AREA IN STORE = ','F6.1,5X,'HARVESTING TIME = ',I2,' DAYS')
WRITE(5,325)
325   FORMAT(15X,'SUMMARY RESULTS FOR EACH DAY OF THE SEASON'/
1   5X,'DAY',5X,'RAIN',5X,'ACUT',5X,'ARAK',5X,'ABAL',
2   5X,'ACAR',5X,'TCUT',5X,'TRAK',5X,'TBAL',5X,'TCAR'/)
DO 600 I = NS(M),IDAY,1
WRITE(5,326) I,RAIN(I),ACUT(I),ARAK(I),ABAL(I),ACAR(I),
1   TCUT(I),TRAK(I),TBAL(I),TCAR(I)
600 CONTINUE
ENDIF
RETURN
END

C******************************************************************************
C******************************************************************************
SUBROUTINE RESULT
C******************************************************************************
C**********************************************************************
C THIS SUBROUTINE WRITES THE SUMMARY RESULTS.
COMMON/B1/ NDAYS, ITYPE, DATE(100), RAIN(100), VPDN(100),
1   RN(100), TN(100), VPD(100,20), W(100,20),
2   RG(100,20), R(100,20), T(100,20)
COMMON/B2/ IDAY, AREA1, NP(4), LDAYC, MAN, NIT, WR(4), NM(4), NT(4),
1   IHD, RMIC, BMIC, RP(8), AR(4,200), XMC(4,200),
2   YD(4,200), IOP(4), ICART, NOP, ARP, ISAL, DSTMN, DSTMX
COMMON/B3/ YIELD, DIGEST, XIMC, DST(4,200), CRAIN(3,200),
1   RNDW(3,200), XMINMC(3,200), TRAIN(3,200), ASTORE
COMMON/B4/ IHR, ICOND, IBALE
COMMON/B5/ IYEAR, NBS(25), AREA, IDAYB
COMMON/B6/ LP
COMMON/B7/ NYEARS, NREPL, IREPL
COMMON/B8/ AST(25,10), AUF(25,10), AUT(25,10),
1   ASWATH(25,10), ABALED(25,10), DM(25,10),
2   DDM(25,10), IHDAYS(25,10)
COMMON/B10/ ACUT(100), ARAK(100), ABAL(100), ACAR(100), TCUT(100),
1   TRAK(100), TBAL(100), TCAR(100)
DIMENSION ASTI(25), AUF1(25), AUT1(25), ASWATH1(25),
1   ABALE1(25), DM1(25), DDM1(25), IHDAYS1(25)
DIMENSION XD(25,10), XD1(25)
CHARACTER DATE*6

C
WRITE(3,300) AREA, MAN
300   FORMAT(1'/45X,'SIMULATION RESULTS'//20X,
1   'AREA = ','F5.1,' HA'//20X,II, '-MAN FARM')
IF(ICART .EQ. 0) WRITE(3,330)
IF(ICART .EQ. 1) WRITE(3,331)
IF(ICART .EQ. 2) WRITE(3,332)
330   FORMAT(20X,'NO CARTING - BALES STORED IN THE FIELD')
331   FORMAT(20X,'CONTRACT CARTING')
332   FORMAT(20X,'CARTING DONE BY ON-FARM LABOUR')
IF(ICOND .EQ. 0) THEN
WRITE(3,301)
ELSE
WRITE(3,302)
ENDIF
301   FORMAT(20X,'UNCONDITIONED HAY')
302 FORMAT(/20X,'CONDITIONED HAY')
   IF(IBALE .EQ. 1) THEN
      WRITE(3,303)
   ELSE
      WRITE(3,304)
   ENDIF
303 FORMAT(/20X,'RECTANGULAR BALES')
304 FORMAT(/20X,'ROUND BALES')
   WRITE(3,305) DTMAX, DSTEMIN, ARP, ISAL
305 FORMAT(/'20X,'MAXIMUM DIGESTIBILITY = ','F4.2//'20X,
   1       'MINIMUM DIGESTIBILITY = ','F4.2//'20X,
   2       'PROBABILITY OF 3 DRY DAYS = ','F3.1//'20X,
   3       'SWATH AREA LIMIT = ',II,'-'DAY HARVEST')
   WRITE(3,306) NTT
306 FORMAT(/'20X,'HAY-MAKING MACHINERY//'20X,'TRACTORS = ',II//
   1       '20X,'OPERATION',3X,'WORK RATE',4X,'MEN',3X,'TRACTORS/')
   WRITE(3,307) WK(1),NM(1),NT(1)
   WRITE(3,308) WR(2),NM(2),NT(2)
   WRITE(3,309) WR(3),NM(3),NT(3)
   IF(ICART .EQ. 2) WRITE(3,310) WR(4),NM(4),NT(4)
307 FORMAT(20X,'CUTTING',5X,F4.1,1X,'HA/HR',5X,II,7X,II)
308 FORMAT(20X,'REAPING',6X,F4.1,1X,'HA/HR',5X,II,7X,II)
309 FORMAT(20X,'BAILING',6X,F4.1,1X,'T/HR',6X,II,7X,II)
310 FORMAT(20X,'CARTING',5X,F4.1,1X,'T/HR',6X,II,7X,II)
   IF(LP .EQ. 4) GO TO 10
   IF(NREPL .EQ. 1) GO TO 5
C*****WRITE THE RESULTS (YEAR WISE)
   DO 500 M = 1,NYEARS
      WRITE(3,311) M,DATE(NS(M))
311 FORMAT('1',5X,'YEAR = ',II,5X,'START DATE = ',A6)
   WRITE(3,312)
312 FORMAT(/'5X,'REPLI-',3X,'AREA',6X,'UNFINISHED',5X,'UNCUT',
   1      '5X,'AREA',9X,'BALED',9X,'DRY',8X,'DIGESTIBLE',5X,
   2      'DAYS'/5X,'CATION',3X,'IN',8X,'AREA',11X,'AREA',6X,
   3      'LYING',8X,'AREA',10X,'MATTER',5X,'DRY MATTER',5X,
   4      'REQUIRED'/14X,'STORE',5X,'(HA)',11X,'(HA)',6X,
   5      'IN SWATH',5X,'IN FIELD',6X,'(TONNES)',3X,'(TONNES)',
   6      '7X,'TO COMPLETE'/14X,'(HA)',31X,'(HA)',9X,'(HA)',36X,
   7      'HARVEST/')
   DO 490 N = 1,NREPL
      WRITE(3,313) N,AST(M,N),AUF(M,N),AUCT(M,N),AUNTH(A(M,N),
   1      ABALE(M,N),DM(M,N),DAM(M,N),IDAYS(M,N)
313 FORMAT(7X,I2,F9.1,F14.1,F10.1,F12.1,3F14.1,II4)
490 CONTINUE
500 CONTINUE
5 CONTINUE
C*****WRITE THE RESULTS (REPLICATION WISE)
   DO 510 N = 1,NREPL
      WRITE(3,314) N
314 FORMAT('/5X,YEAR',5X,'START',5X,'AREA',6X,'UNFINISHED',5X,
   1      'UNCUT',5X,'AREA',9X,'BALED',9X,'DRY',8X,'DIGESTIBLE',5X,
   2      'DAYS'/14X,'DATE',6X,'IN',8X,'AREA',11X,'AREA',6X,
   3      'LYING',8X,'AREA',10X,'MATTER',5X,'DRY MATTER',5X,
   4      'REQUIRED'/24X,'STORE',5X,'(HA)',11X,'(HA)',6X,
   5      'IN SWATH',5X,'IN FIELD',6X,'(TONNES)',3X,'(TONNES)',
   6      '7X,'TO COMPLETE'/24X,'(HA)',31X,'(HA)',9X,'(HA)',36X,
7 'HARVEST')
DO 505 M = 1,NYEARS
WRITE (3,316) M,DATE(NS(M)),AST(M,N),AUF(M,N),AUCT(M,N),
1 ASWATH(M,N),ABALED(M,N),DM(M,N),DDM(M,N),IHDAYS(M,N)
316 FORMAT(7X,I2,4X,A6,F9.1,F14.1,F10.1,F12.1,3F14.1,14)
505 CONTINUE
510 CONTINUE
10 CONTINUE
IF(NYEARS .EQ. 1) GO TO 15
C*****DETERMINE AVERAGE OF ALL REPLICATIONS FOR EACH YEAR.
C ALSO DETERMINE THE AVERAGE, MINIMUM, MAXIMUM AND STANDARD
C DEVIATION OF EACH PARAMETER BASED ON NYEARS.
CALL SUMMARY(NYEARS,NREPL,AST,AST1,AST2,AST3,AST4,AST5)
CALL SUMMARY(NYEARS,NREPL,AUF,AUF1,AUF2,AUF3,AUF4,AUF5)
CALL SUMMARY(NYEARS,NREPL,AUCT,AUCT1,AUCT2,AUCT3,AUCT4,AUCT5)
CALL SUMMARY(NYEARS,NREPL,ASWATH,ASWATH1,ASWATH2,ASWATH3,
1 ASWATH4,ASWATH5)
CALL SUMMARY(NYEARS,NREPL,ABALED,ABALED1,ABALED2,ABALED3,
1 ABALED4,ABALED5)
CALL SUMMARY(NYEARS,NREPL,DM,DM1,DM2,DM3,DM4,DM5)
CALL SUMMARY(NYEARS,NREPL,DDM,DDM1,DDM2,DDM3,DDM4,DDM5)
DO 520 M = 1,NYEARS
DO 515 N = 1,NREPL
XD(M,N) = IHDAYS(M,N)
515 CONTINUE
520 CONTINUE
CALL SUMMARY(NYEARS,NREPL,XD,XD1,XD2,XD3,XD4,XD5)
DO 525 M = 1,NYEARS
IHDAYS1(M) = XD1(M)
525 CONTINUE
IHDAYS2 = XD2
IHDAYS3 = XD3
IHDAYS4 = XD4
IHDAYS5 = XD5
C*****WRITE THE SUMMARY RESULTS
WRITE (3,320) NREPL
320 FORMAT('1',40X,'AVERAGE OF ',I2,' REPLICATIONS')
WRITE (3,315)
DO 530 M = 1,NYEARS
WRITE (3,316) M,DATE(NS(M)),AST1(M),AUF1(M),AUCT1(M),
1 ASWATH1(M),ABALED1(M),DM1(M),DDM1(M),IHDAYS1(M)
530 CONTINUE
WRITE (3,321) AST2,AUF2,AUCT2,ASWATH2,ABALED2,DM2,DDM2,IHDAYS2
WRITE (3,322) AST3,AUF3,AUCT3,ASWATH3,ABALED3,DM3,DDM3,IHDAYS3
322 FORMAT(//2X,'MINIMUM',F19.1,F14.1,F10.1,F12.1,3F14.1,14)
WRITE (3,323) AST4,AUF4,AUCT4,ASWATH4,ABALED4,DM4,DDM4,IHDAYS4
323 FORMAT(//2X,'MAXIMUM',F19.1,F14.1,F10.1,F12.1,3F14.1,14)
WRITE (3,324) AST5,AUF5,AUCT5,ASWATH5,ABALED5,DM5,DDM5,IHDAYS5
15 CONTINUE
RETURN
END
C******************************************************************************
SUBROUTINE SUMMARY(NYEARS,NREPL,BAR,BAR1,BAR2,BAR3,BAR4,BAR5)
C THIS SUBROUTINE DETERMINES AVERAGE VALUE OF A GIVEN VARIABLE
C FOR EACH YEAR. IT ALSO DETERMINES THE AVERAGE, MINIMUM,
C  MAXIMUM AND STANDARD DEVIATION OF EACH VARIABLE.
C  DIMENSION VAR(25,10),VAR1(25)
C  VARIABLES USED ARE:
C  NYEARS = NO. OF YEARS
C  NREPL = NO. OF REPLICATIONS FOR EACH YEAR
C  VAR(M,N) = VALUE OF VARIABLE FOR MTH YEAR & NTH REPLICATION
C  VAR1(M) = AVERAGE VALUE OF VARIABLE FOR MTH YEAR
C  AVG = AVERAGE VALUE OF GIVEN VARIABLE
C  XMIN = MINIMUM VALUE OF GIVEN VARIABLE
C  XMAX = MAXIMUM VALUE OF GIVEN VARIABLE
C  SD = STANDARD DEVIATION OF GIVEN VARIABLE
C*****DETERMINE AVERAGE VALUE OF VARIABLE FOR EACH YEAR
   DO 505 M = 1,NYEARS
      SUM = 0.0
      DO 500 N = 1,NREPL
         SUM = SUM + VAR(M,N)
   500 CONTINUE
      VAR1(M) = SUM/NREPL
   505 CONTINUE
C*****DETERMINE AVERAGE, MINIMUM & MAXIMUM VALUES OF EACH VARIABLE
   SUM = 0.0
   XMIN = VAR1(1)
   XMAX = VAR1(1)
   DO 510 M = 1,NYEARS
      SUM = SUM + VAR1(M)
      IF(XMIN .GT. VAR1(M)) XMIN = VAR1(M)
      IF(XMAX .LT. VAR1(M)) XMAX = VAR1(M)
   510 CONTINUE
   AVG = SUM/NYEARS
C*****DETERMINE STANDARD DEVIATION (SD)
   SUM = 0.0
   DO 520 M = 1,NYEARS
      DIFF = VAR1(M) - AVG
      SUM = SUM + DIFF**2
   520 CONTINUE
   SD = SQRT(SUM/(NYEARS-1))
RETURN
END
A SAMPLE OUTPUT OF THE PROGRAM HAYSIM

SIMULATION RESULTS

AREA = 50.0 HA
2-HAN FARM
CARTING DONE BY ON-FARM LABOUR
UNCONDITIONED HAY
RECTANGULAR BALES

MAXIMUM DIGESTIBILITY = 0.64
MINIMUM DIGESTIBILITY = 0.50
PROBABILITY OF 1 DRY DAYS = 0.3
SWATH AREA LIMIT = 2-DAY HARVEST

HAY-MAKING MACHINERY

TRACTORS = 2

OPERATION WORK RATE MEN TRACTORS
CUTTING 2.0 T/HR 1 1
RACKING 3.0 T/HR 1 1
BALEING 6.0 T/HR 1 1
CARTING 4.0 T/HR 2 0

AVERAGE OF 5 REPLICATIONS

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<tr>
<th>YEAR</th>
<th>START DATE</th>
<th>AREA</th>
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<th>LOST</th>
<th>AREA</th>
<th>BAILED</th>
<th>DRY MATTER</th>
<th>DIGESTIBLE DRY MATTER</th>
<th>DAYS REQUIRED TO COMPLETE HARVEST</th>
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AVERAGE 50.0 0.0 0.0 0.0 177.1 93.8 34

MINIMUM 50.0 0.0 0.0 0.0 86.8 37.5 16

MAXIMUM 50.0 0.0 0.0 0.0 270.7 150.8 47

S. DEV. 0.0 0.0 0.0 0.0 66.3 39.6 8
APPENDIX B

LISTING OF THE COMPUTER PROGRAM PASTURE

PROGRAM PASTURE
C THIS PROGRAM PREDICTS THE YIELD, DIGESTIBILITY AND DIGESTIBLE DRY MATTER OF STANDING PASTURE KEPT FOR HAYMAKING.
DIMENSION YIELD(25,52),DIGEST(25,52),DDM(25,52)
COMMON/B1/ RAIN(365),EVAP(365),TEMP(52),SU(365),SL(365),
1 SM(365)
COMMON/B2/ SRF,SLF,SUW,SLW,PR,WP
COMMON/B3/ PG,PD,DD,SG
COMMON/B4/ N,ND,D,NG,NF
COMMON/B5/ S宛,SMF,WRAIN,NWSF,WPET,DL,TG
INTEGER YEAR,CYEAR
OPEN (UNIT=1,FILE='PASTURE.DAT',STATUS='OLD',DISPOSE='SAVE')
OPEN (UNIT=2,FILE='WEATHER1.DAT',STATUS='OLD',DISPOSE='SAVE')
OPEN (UNIT=3,FILE='PASTURE1.OUT',STATUS='NEW',DISPOSE='SAVE')
OPEN (UNIT=4,FILE='PASTURE2.OUT',STATUS='NEW',DISPOSE='SAVE')
OPEN (UNIT=5,FILE='PASTURE3.OUT',STATUS='NEW',DISPOSE='SAVE')

C*****READ INPUT DATA
C*****GENERAL DATA
C NP = WEEK OF THE YEAR WHEN THE PADDOCK WAS CLOSED
C NYB = STARTING YEAR OF SIMULATION (19..)
C NYF = FINISHING YEAR OF SIMULATION (19..)
READ(1,*) NP, NYB, NYF

C*****SOIL DATA
C SRF = CAPACITY OF UPPER SOIL MOISTURE ZONE, mm
C SLF = CAPACITY OF LOWER SOIL MOISTURE ZONE, mm
C SUW = WILTING POINT OF UPPER SOIL LAYERS, mm
C SLW = WILTING POINT OF LOWER SOIL LAYERS, mm
READ (1,*) SRF, SLF, SUW, SLW

C*****STARTING VALUES FOR SOIL AND PASTURE
C SUI = SOIL MOISTURE LEVEL IN THE UPPER LAYER, mm
C SLY = SOIL MOISTURE LEVEL IN THE LOWER LAYER, mm
C PGI = QUANTITY OF GREEN PASTURE AVAILABLE, kg/ha
C PDI = QUANTITY OF DEAD PASTURE AVAILABLE, kg/ha
C DDI = DIGESTIBILITY OF DEAD PASTURE, DECIMAL
READ (1,*) SUI, SLY, PGI, PDI, DDI

C CALCULATE FIELD CAPACITY (FC) AND WILTING POINT (WP)
FC= SRF + SLF
WP= SUW + SLW

C DETERMINE THE TOTAL NO. OF YEARS (NYEAR)
NYEAR = NYF - NYB + 1

C RUN MODEL FOR NYEAR
C CYEAR = CURRENT YEAR (EX. 1968)
C YEAR = NO. OF YEAR (EX. 1, 2, 3...16)
CYEAR = NYB - 1
YEAR = 0
C PROCEED TO FOLLOWING YEAR
5 CONTINUE
YEAR = YEAR + 1
CYEAR = CYEAR + 1
WRITE(3,200) CYEAR
WRITE(4,200) CYEAR
200 FORMAT('1'///5X,'YEAR = ',I4)
WRITE(3,201)
201 FORMAT('///15X,'YIELD AND DIGESTIBILITY OF PASTURE'///
1 5X,'WEEK',6X,'YG',6X,'YD',6X,'DG',6X,'DD',3X,'YIELD',2X,
1 'DIGEST',5X,'DOM')
WRITE(4,300)
300 FORMAT('///15X,'DETAILED RESULTS OF PASTURE GROWTH MODEL',
1 ///3X,'WEEK',3X,'NWSF',3X,'TEMP',3X,'RAIN',2X,'WPET',2X,
2 'SMAF',3X,'SMF',6X,'DW',6X,'PG',5X,'TCD',6X,'PD',4X,
3 'TPAS',4X,'DG',4X,'DD',5X,'YIELD',4X,'DIGEST')
C*****READ THE WEATHER DATA FOR THIS YEAR
C RAIN(I) = RAIN ON ITH DAY, MM
C EVAP(I) = EVAPORATION ON ITH DAY, MM
C TEMP(K) = AVERAGE TEMPERATURE FOR KTH WEEK, DEG C
READ(2,100) (RAIN(I),I = 247,365)
READ(2,100) (EVAP(I),I = 247,365)
READ(2,101) (TEMP(K),K = 36,52)
100 FORMAT(3X,12F5.1)1X,11F5.1)
101 FORMAT(3X,12F5.1/1X,5F5.1)
C CALCULATE THE NO. OF STARTING DAY
N = NP
N1 = 365 - (52-N+1)*7
ND = N1 + 1
C CALCULATE THE NO. OF WEEK SINCE GERMINATION (NG)
NG = N - 25
C SET THE INITIAL VALUES FOR PASTURE AND SOIL
PG = PGI
PD = PDI
DD = DDI
SDG = 0.87
SU(N1) = SUI
SL(N1) = SLI
C CALCULATE SOIL MOISTURE ON DAY N1
SM(N1) = SU(N1) + SL(N1)
C CALCULATE "SMAF"
SMAF = (SM(N1)-WP)/(FC-WP)
NF = 45
NWSF = 0
N = N-1
10 CONTINUE
C*****PROCEED TO FOLLOWING WEEK
N= N+1
NDL= ND+6
D = FLOAT(ND)
C CALCULATE THE WEEKLY RAINFALL(MM)
WRAIN = 0.0
DO 500 I = ND,NDL
WRAIN = WRAIN + RAIN(I)
500 CONTINUE
C
C*****CALL THE GROWTH SUBROUTINE
CALL GROWTH
C
C*****CALCULATE YIELD AND DIGESTIBILITY OF PASTURE
C
YG = YIELD OF GREEN PASTURE, t/ha
YD = YIELD OF DEAD PASTURE, t/ha
YIELD = TOTAL YIELD OF PASTURE, t/ha
DIGEST = AVERAGE DIGESTIBILITY OF PASTURE, DECIMAL
DDM = DIGESTIBLE DRY MATTER, t/ha
TPAS = TOTAL AMOUNT OF PASTURE (KG)
TPAS = PG + PD
YG = PG/1000.
YD = PD/1000.
YIELD(YEAR,N) = YG+YD
DIGEST(YEAR,N) = (DG * YG + DD * YD) / YIELD(YEAR,N)

MAKE AN ADJUSTMENT IN THE YIELD FOR STUBBLE HEIGHT
YIELD(YEAR,N) = YIELD(YEAR,N) - 0.5
DDM(YEAR,N) = YIELD(YEAR,N) * DIGEST(YEAR,N)

C
C ***WRITE THE RESULTS
C
WRITE (3,202) N, YG, YD, DG, DD, YIELD(YEAR,N), DIGEST(YEAR,N),
1       DDM(YEAR,N)
202 FORMAT (7X, I2, 7F8.3/)
WRITE (4, 301) N, NWSF, TEMP(N), WRAIN, WPFT, SMAF, SMF, DW, PG,
1       TCG, PD, TPAS, DG, DD, YIELD(YEAR,N),
2       DIGEST(YEAR,N)
301 FORMAT (21H7.1, F6.1, 2F6.2, 5F8.0, 2F6.3, 2F10.3/)
ND = ND + 1
IF (N .LT. 52) GO TO 10
IF (YEAR .LT. NYEAR) GO TO 5

C
C CALCULATE AVERAGE YIELD, DIGESTIBILITY AND DIGESTIBLE
C DRY MATTER.

C
WRITE (3,203)
WRITE (4,203)
203 FORMAT ('1', /'///5X, 'AVERAGE PASTURE GROWTH VALUES'//
1      5X, 'WEEK', 6X, 'AVG YIELD', 5X, 'AVG DIGEST', 5X,
2      'DIGEST D.M. ')

C
DO 405 N = 36, 52
SYIELD = 0.0
SDDIGEST = 0.0
SDDM = 0.0
DO 400 YEAR = 1, NYEAR
SYIELD = SYIELD + YIELD(YEAR,N)
SDDIGEST = SDDIGEST + DIGEST(YEAR,N)
SDDM = SDDM + DDM(YEAR,N)
400 CONTINUE
C
AYIELD = AVERAGE YIELD OF PASTURE, t/ha
ADIGEST = AVERAGE DIGESTIBILITY OF PASTURE, DECIMAL
ADDM = AVERAGE DIGESTIBLE DRY MATTER, t/ha
AYIELD = SYIELD/NYEAR
ADIGEST = SDDIGEST/NYEAR
ADDM = SDDM/NYEAR

C
WRITE (3,204) N, AYIELD, ADIGEST, ADDM
WRITE (4,204) N, AYIELD, ADIGEST, ADDM
204 FORMAT (I9,3F15.3)
405 CONTINUE
WRITE THE RESULTS FOR FINDING REGRESSION EQUATIONS
DO 700 YEAR = 1,NYEAR
WRITE(5,206) YEAR
206 FORMAT(1x,'YEAR = ',I2)
DO 690 N = 39,52
 I = (N - 39) * 7 + 1
WRITE(5,207) I,YIELD(YEAR,N),DIGEST(YEAR,N)
207 FORMAT(1x,I2,2F7.3)
690 CONTINUE
700 CONTINUE
STOP
END

SUBROUTINE GROWTH

DIMENSION GP(52)
COMMON/B1/ RAIN(365),EVAP(365),TEMP(52),SU(365),SL(365),
  1 SM(365)
COMMON/B2/ SUD,SLE,SUW,SLW,FC,WP
COMMON/B3/ PG,PD,DD,SDG
COMMON/B4/ N,ND,D,NG,WP
COMMON/B5/ SMAF,SMF,WRAIN,NWSF,WPET,DW,TGD
  2 132.,135.,138.,141./*
DATA PIK,PER,CDR,WM,IMX,WTN1,NWSF/0.017214,20.0,3.0,3.0,1.0,1.5,1.0,20.0,20.0,2000.0,1.5/
DATA DKM,DKMM,PG,CFRT/20.0,20.0,2000.0,1.5/

THIS SUBROUTINE SIMULATES THE PASTURE GROWTH RATE,
SENESCENCE AND DECOMPOSITION. GREEN AND DEAD HERBAGE
POOLS ARE ASSUMED. THE DIGESTIBILITY OF THE PASTURE
HERBAGE IS ALSO PREDICTED.

SPECIFY SEASONAL CURVE FOR MAXIMUM POSSIBLE PASTURE GROWTH RATE (GP)
I.E. SOIL MOISTURE IS ASSUMED NOT TO BE LIMITING GROWTH
SPECIFY RELATIONSHIP BETWEEN GP AND THE AVAILABILITY (W1)
AT WHICH GP OCCURS, I.E. AT WHICH GROWTH RATE IS MAXIMIZED

GPN = 0.8 * GP(N)
IF (N.GT.NF) GPN = GPN*0.70
IF (TEMP(N).LT.10.0) GPN = GPN*(0.0143*TEMP(N)**2-0.43)
GPN = NMAX1(GPN,0.0)
W1 = 1000. + 13.0*GPN
W2 = 350. + 33.0*GPN
IF (PG.LT.W1. OR .GPN.LT.30) GO TO 60
IF (PG.LT.W1) W1 = W2
IF (PG.LE.W2) W1 = PG
60 C = 1./W1
A = GPN*C*EXP(1.)
DLIG = WM
TGD = 0.0
WAST = 0.0
WPET = 0.0
WSMF = 0.0
WSMAF = 0.0
WM = 0.0
TGR = 0.0

250
DKM = 0.0
WSMC = 0.0
NX = 7
ND = ND-1
NH = ND+NX
WNX = FLOCAT(NX)
30 ND = ND+1
NL = ND-1
C
C ASSUME PLANTS HAVE A POTENTIAL MOISTURE TRANSMISSION
C (TRANSPIRATION) RATE.
C ASSUME THAT TM IS LINEARLY RELATED TO AVAILABLE SOIL MOISTURE
TM = AMAX1(0.035, SMAF*IMX)
C DETERMINE ACTUAL EVAPOTRANSPIRATION (AET)
PET = EVAP(ND) * 0.85
C PREDICT DAYLENGTH (DL)
DL = 11.97 - 2.47*SIN(PIK*(D-80.))
Z = 1.35*PET/DL
IF (TM.GE.2) GO TO 1
B = TM*DL*DL/(6.75*PET) + 0.06*DL
AEP = TM*(DL-B)
GO TO 2
1 AEP = PET
2 CONTINUE
C REDUCE ACTUAL EVAPOTRANSPIRATION AT LOW HERBAGE AVAILABILITIES
IF (NG.LT.2) AET = AEP*(1.0-EXP(-1.5*PG/1000.))
IF (NG.GE.2) AET = AEP*(1.0-EXP(-1.0*PG/1000.))
WAET = WAET + AET
WPET = WPET + PET
C ASSUME GROWTH LINEARLY RELATED TO ACTUAL EVAPOTRANSPIRATION
C CHECK FOR PET .EQ. ZERO
IF (PET.EQ. 0.0) GO TO 50
SMF = AEP/PET
WSMF = WSMF + SMF
WSMC = WSMC + 1.0
50 CONTINUE
C
C*****UPDATE UPPER AND LOWER SOIL MOISTURE ZONES
SU(ND) = SU(NL)+AMIN1(RAIN(ND), 40.0)-AET
IF (SU(ND).GE.SUW. OR .SU(ND).GE.SU(N1)) GO TO 65
SL(N1) = SL(N1)+SU(ND)-SU(N1)+AMAX1(SU(N1)-SUW, 0.0)
SU(ND) = AMIN1(SU(N1), SUW)
65 TP = PG+PD
TPI = PG + PD/3.
STC = -0.9 + 0.04*WIN1
EL = (SU(N1)/SU)**2*EXP((STC*TP/1000.)*EVAP(ND)
IF (SU(ND).GT.0.0) SU(ND) = AMAX1(0.0, SU(ND)-EL
UGC = SL(N1)*0.4*EXP(11.5*SL(N1)/SLF)/7000000.
SL(ND) = SL(N1) + AMAX1(SU(ND)-SUW, 0.0)-UGD
SU(ND) = AMIN1(SUF, AMAX1(SU(ND), 0.0))
SL(ND) = AMIN1(SUL, SL(ND))
SM(ND) = SU(ND)+SL(ND)
SMAF = AMAX1(SM(ND)-WP, 0.0)
SMAF = SMA/(EC-WP)
WSMAF = WSMAF + SMAF
CR = RAIN(ND)*EXP(-1.0*(DKM/100.))*5
CE = EVAP(ND)*AMIN1(1.0, 2.4-TP/9000.)*DKM/100.
DKM = DKM + CR - CE
WM = WM + RAIN(ND) - EVAP(ND)
DKMM = DKMM + DKM
IF (ND.LT.NH) GO TO 30
DLAG = AMAX1(3.0,AMIN1(4.5,0.75*DLAG+0.25*WM))
DKMM = DKMM/WNX
AET = WAET/WNX
PET = WPET/WNX
SMF = WSMF/WSMC
SMAF = WSMAF/WNX

C
IF(NG .GE. 1) NG = NG + 1
C SET THE VALUE OF FLAG "IGS"
IF(N .LT. NF) IGS = 1
C*****ADVANCE FLOWERING TIME (NF) IF PASTURE DRIES OFF
IF (N.GT.45) GO TO 6
IF (NF.LT.45) GO TO 6
IF (N.EQ.45) GO TO 40
IF (N.LE.37. OR .SMF.GE.0.75) GO TO 6
40 NF = N
NWSF = 1
PGNF = PG
CRT = .15
IGS = 0
6 CONTINUE
C*****ESTIMATE TRANSFER OF GREEN PASTURE TO DRY PASTURE
C POOL (TGD)
IF (N.GT.NF.AND.NG.GT.8) GO TO 10
IF (N.GT.7. OR .PG.LT.40.) GO TO 9
IF (NG.LT.8) GO TO 9
10 CONTINUE
IF(N .LE. 43) THEN
PGMORT = (3.70*EXP(-7*SMF**2)+((NWSF-1)**3)/12.0)*0.007
ELSE
PGMORT = (3.70*EXP(-7*SMF**2)+((NWSF-1)**3)/12.0
1 +(N-43)**2) * 0.007
END IF
TGD = PGMORT*PG
NWSF = NWSF + 1
TGR = AMIN1(CRT,.25*PGMORT)
CRT = CRT - TGR
TGR = PGNF*TGR
9 CONTINUE
RAD = .0001*(11.-10.*SIN((D+74.)*PIK))
WTGD = PG*(RAD*(PG + PD)-1.56)*0.007
TGD = AMAX1(WTGD,TGD)
C*****DETERMINE DIGESTIBILITY OF GREEN PASTURE
TPDG = DG
IF(N .LE. NF) DG=SDG-0.05*(PG/5000.0)**0.5 -N/500.0
IF(N .EQ. NF) SDG=DG
IF(N .GT. NF) DG=SDG-0.01*NWSF-0.001*NWSF**2
DG = AMAX1(DG,0.65)
IF (IGS.EQ.0) DG = AMIN1(DG,TPDG)
20 IF (NG.LE.2) DG = 0.75
25 CONTINUE
C*****DETERMINE DIGESTIBILITY OF DEAD PASTURE
SMA = AMAX1(0.0,(SU(ND)-SUL)/(SU-F-SUL))
SMAL = AMAX1(0.0,(SL(ND)-(SL+10))/(SL-SL)),
SULMF = AMAX1(SMAF**2,SMAL)
IF (N.GT.NF .AND. N-NF.LT.4) DD = DD+0.01*(N-NF)**2
IF (N.EQ.NF+4) DD= 0.55-0.06*(1-EXP(-0.06*((PG+PD)/1000.)*2))
DDD= AMAX1(0.025*DD**3,0.016*SMAU)
DD= AMAX1(DD-DDD, 0.35)

**DETERMINE DECOMPOSITION FACTOR (DKPF)**
DKTF= 1.-EXP(-.15*(TEMP(N)-5.0))
DKMF= 1.-EXP(-DLAG*DKMM/100.)
DKAF= .4 + .6*EXP(-3.5*CDR/10.)
DKPF= 0.5*DKTF*DKAF*DKMF**2
CDR= CDR + DKPF
DDCP = PD*DKPF

**PREDICT PASTURE GROWTH RATE (DW, KG/HA/DAY)**
IF (NG.LE.1) DW= PER*SULMF
IF (NG.GT.1) DW= PG*A*EXP(-C*PG)*SMF

**UPDATE AVAILABILITIES OF GREEN AND DEAD PASTURE (PG & PD)**
PG = PG - TGD - TGR + DW * 7.0
PG= AMAX1 (PG,0.0)
IF (NG.GT.10. AND .PG.LT.40.) PG= AMAX1(PG,30.0)
IF (NG.GT.10 .AND. PG.LT.40.) NG= 0
PD= PD+TGD-DDCP
PD = AMAX1 (PD,0.0)
WIN1= TEMP(N)
RETURN
END
### APPENDIX C

**PASTURE GROWTH DATA FOR 16 YEARS**

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Field drying experiments were carried out during the hay-making season in 1983 at the Animal Research Institute in Werribee, Victoria. The reduced data are presented in this appendix. Tables D.1 and D.2 list the drying data of hay when it contained the original plant water and rain/dew water respectively. Table D.3 shows the rewetting data due to rain. The data given in Table D.4 pertains to the change in moisture content during a rain-free night. The description of the variables used in these tables is given as follows:

\begin{itemize}
  \item \textbf{CMN} = change in moisture content during a rain-free night, \% dry basis
  \item \textbf{COND} = conditioning dummy variable, its value is 0 for unconditioned hay and 1 for conditioned hay
  \item \textbf{DR} = average hourly drying rate, \% decrease in moisture content (dry basis) per hour
  \item \textbf{IMR} = increase in moisture content due to rain, \% dry basis
  \item \textbf{M} = moisture content at the beginning of hour, \% dry basis
  \item \textbf{MBR} = moisture content at the beginning of rainfall, \% dry basis
  \item \textbf{ME} = moisture content at the end of the day, \% dry basis
  \item \textbf{MVPD} = mean vapour pressure deficit during the hour, kPa
  \item \textbf{R} = amount of rainfall, mm
  \item \textbf{RG} = global radiation during the hour, MJ m\(^{-2}\)
  \item \textbf{RK} = raking dummy variable, its value is 0 for the unraked hay and 1 for the raked hay
  \item \textbf{VPDN} = average hourly vapour pressure deficit during the night, kPa
  \item \textbf{W} = wind speed during the hour, m s\(^{-1}\)
  \item \textbf{WN} = average wind speed during the night, m s\(^{-1}\)
  \item \textbf{Y} = yield of pasture (dry matter), t ha\(^{-1}\)
\end{itemize}
Table D.1  Drying data of hay when it contained original plant water only.

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APPENDIX E

BALED HAY DRYING DATA

A drying experiment was conducted during the hay-making season in 1985. The purpose of the experiment was to investigate the effect of weather on the drying rate of wet bales. The reduced data are given in Table E.1. The description of the symbols used is as follows:

\[ DR \quad = \quad \text{average hourly drying rate, \% decrease in moisture content (dry basis) per hour} \]

\[ M \quad = \quad \text{moisture content at the beginning of hour, \% dry basis} \]

\[ MVPD \quad = \quad \text{mean vapour pressure deficit during the hour, kPa} \]
Table E.1  Drying data of wet hay bales.

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APPENDIX F

INCREASE IN MOISTURE CONTENT OF BALES DURING RAIN

Let

\[ L = \text{length of bale, mm} \]
\[ W = \text{width of bale, mm} \]
\[ R_{i,j} = \text{amount of rainfall during } j^\text{th} \text{ hour on } i^\text{th} \text{ day after baling, mm} \]
\[ W_d = \text{dry matter weight of bale, kg} \]
\[ W_w = \text{weight of water absorbed by the bale, kg} \]
\[ CM_{i,j} = \text{change in moisture content during } j^\text{th} \text{ rainy hour on } i^\text{th} \text{ day after baling, } \% \text{ dry basis} \]

Assuming that only 80% of rain falling on the bale is absorbed, then

\[ W_w = 0.8 \times L \times W \times R_{i,j} \times 10^{-6} \]

\[ CM_{i,j} = \frac{(W_w \times 100)}{W_d} = \frac{(0.8 \times L \times W \times R_{i,j} \times 10^{-6} \times 100)}{W_d} \]

By taking \( L = 1000 \text{ mm}, W = 500 \text{ mm} \) and \( W_d = 20 \text{ kg} \), we get

\[ CM_{i,j} = 2.0 R_{i,j} \]
APPENDIX G

RESPIRATION DATA

Figure G.1 shows the effect of dry matter (DM) content and air temperature on dry matter loss due to respiration. Table G.1 gives the data which were obtained by reading off the values from each curve.

![Graph showing effect of dry matter content and air temperature on respiration loss.](image)

**Figure G.1** Effect of dry matter (DM) content on respiration loss at different temperatures (from Honig, 1980).
Table G.1 Respiration data.

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Let \( DDM_1 = \text{digestible dry matter yield of hay at the beginning of a mechanical operation, t ha}^{-1} \)

\( D_1 = \text{digestibility of hay at the beginning of a mechanical operation} \)

\( DM_1 = \text{dry matter yield of hay at the beginning of a mechanical operation, t ha}^{-1} \)

Then, \( DDM_1 = DM_1 \times D_1 \) \hspace{1cm} (B.1)

If \( a_m \) is the fractional dry matter loss due to a mechanical operation, then the digestible dry matter yield of hay at the end of the operation \( (DDM_2) \) can be given as follows:

\( DDM_2 = (1 - a_m) DM_1 \times D_2 \) \hspace{1cm} (B.2)

where \( D_2 = \text{digestibility of hay at the end of the mechanical operation} \)

Assuming that the digestibility of material lost due to a mechanical operation is 20% higher than the remaining material, we have

\( DDM_2 = DDM_1 - a_m \times DM_1 \times 1.2 \times D_1 \) \hspace{1cm} (B.3)
Equating Equations B.2 and B.3, and substituting the value of 
\( DDM_1 \) from Equation B.1, we get

\[
(1 - a_m) \times D_M \times D_2 = D_M \times D_1 \times (1 - 1.2 a_m)
\]

Or

\[
D_2 = \frac{D_1 \times (1 - 1.2 a_m)}{1 - a_m}
\]  \( \text{(B.4)} \)

Now, the fractional loss of digestibility due to the mechanical 
operation, \( b_m \), can be determined as follows:

\[
b_m = \frac{D_1 - D_2}{D_1}
\]  \( \text{(B.5)} \)

From Equations B.4 and B.5, we get

\[
b_m = \frac{0.2 a_m}{1 - a_m}
\]  \( \text{(B.6)} \)
APPENDIX I

CHANGES IN DIGESTIBILITY DUE TO ENVIRONMENTAL FACTORS

Let \( DDM_b \) = digestible dry matter yield of hay before it is affected by respiration or leaching as appropriate, \( t \text{ ha}^{-1} \)

\( D_b \) = digestibility of hay before it is affected by respiration/leaching

\( DM_b \) = dry matter yield of hay before it is affected by respiration/leaching, \( t \text{ ha}^{-1} \)

Then, \[ DDM_b = DM_b \times D_b \] (C.1)

If \( a_e \) is the fractional dry matter loss due to respiration/leaching, then the digestible dry matter yield of hay after it is affected by respiration/leaching (\( DDM_a \)) can be given as follows:

\[ DDM_a = (1 - a_e) \times DM_b \times D_a \] (C.2)

where \( D_a \) = digestibility of hay after it is affected by respiration/leaching

Since the material lost due to respiration/leaching is 100% digestible, we also have

\[ DDM_a = DDM_b - a_e \times DM_b \times 1.0 \] (C.3)
Equating Equations C.2 and C.3, and substituting the value of DDM$_b$ from Equation C.1, we get

$$(1 - a_e) \times DM_b \times D_a = DM_b \times (D_b - a_e)$$

Or

$$D_a = \frac{D_b - a_e}{1 - a_e} \hspace{1cm} (C.4)$$

Now, the fractional loss of digestibility due to respiration/leaching, $b_e$, can be determined as follows:

$$b_e = \frac{D_b - D_a}{D_b} \hspace{1cm} (C.5)$$

From Equations C.4 and C.5, we get

$$b_e = \frac{D_b - (D_b - a_e)/(1 - a_e)}{D_b} \hspace{1cm} (C.6)$$
APPENDIX J

WEATHER FORECAST DATA

Tables J.1 to J.5 give the weather forecast data for five years (1980-1984) which were obtained from the Bureau of Meteorology, Melbourne. Each year's data cover the period from 1 October to 1 December. The definitions of various symbols used are given below:

\[
\begin{align*}
\text{Day} &= \text{number of days after 30 September} \\
\text{D} &= \text{dry day (if there is no rain)} \\
\text{R} &= \text{rainy day (if there is rain)} \\
\text{Day-1} &= \text{today} \\
\text{Day-2} &= \text{tomorrow} \\
\text{Day-3} &= \text{a day after tomorrow}
\end{align*}
\]
Table J.1 Weather forecast data for the year 1980.

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APPENDIX L

CONVERSION OF THREE-HOURLY RAINFALL DATA INTO ONE-HOURLY DATA

Three-hourly rain can fall in one of the following seven ways:

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<td>D</td>
<td>D</td>
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<td>D</td>
<td>R</td>
</tr>
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<td>R</td>
<td>R</td>
<td>D</td>
</tr>
<tr>
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<td>D</td>
<td>R</td>
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</tr>
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<td>R</td>
<td>D</td>
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</tr>
<tr>
<td>7</td>
<td>R</td>
<td>R</td>
<td>R</td>
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</table>

R = Rain    D = Dry

One-hourly rainfall data (without gaps) were used to determine cumulative probabilities of the above events for each month (October, November, December) for different three-hourly intervals (Tables L.1 to L.3). A computer program was written to convert three-hourly data into one-hourly. The procedure used was as follows. A random fraction was generated and compared with the cumulative probabilities to select an appropriate event. The rainfall was then disaggregated into hourly values accordingly. For each of events 4 to 7, the total rainfall for the 3-hour period was assumed to have been divided equally between those hours in which rain fell. The data for other intervals were not disaggregated as the simulation model uses total rainfall during the night.
### Table L.1 Cumulative probabilities of rain occurrence at different 3-hour intervals during the month of October.

<table>
<thead>
<tr>
<th>Event</th>
<th>3-hour Interval</th>
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<td>(9-12 h)</td>
<td>(12-15 h)</td>
<td>(15-18 h)</td>
<td>(18-21 h)</td>
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<tr>
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<td>0.06</td>
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<td>0.67</td>
<td>0.72</td>
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<tr>
<td>7</td>
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<td>1.00</td>
<td>1.00</td>
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### Table L.2 Cumulative probabilities of rain occurrence at different 3-hour intervals during the month of November.

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<td>(12-15 h)</td>
<td>(15-18 h)</td>
<td>(18-21 h)</td>
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</tr>
<tr>
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<td>0.18</td>
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### Table L.3 Cumulative probabilities of rain occurrence at different 3-hour intervals during the month of December.

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<td>(18-21 h)</td>
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<td>0.16</td>
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<tr>
<td>4</td>
<td>0.37</td>
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<td>0.47</td>
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</table>
Based on the research reported in this thesis, the following papers have been published or submitted for publication.


A Mathematical Model for Field Drying of Pasture Hay

M.L. GUPTA
Post-Graduate Student, University of Melbourne
R.H. MACMILLAN
Senior Lecturer in Agricultural Engineering, University of Melbourne
T.A. McMAHON
Professor of Agricultural Engineering, University of Melbourne
D.W. BENNETT
Senior Lecturer in Transport Engineering, University of Melbourne

SUMMARY Field-drying experiments with unconditioned and conditioned pasture were conducted to develop a simulation model for predicting hay drying time. A drying model (HAYDMO) is described which simulates the moisture content of pasture hay on an hourly basis. It is based on experimental data and includes the effect of rainfall and dew. Multiple regression equations were evolved to estimate hourly drying rate, change in moisture content during the night and increase in moisture content due to rain. HAYDMO can be used with three different combinations of meteorological data: (i) hourly temperatures (dry and wet bulb) and rainfall; (ii) hourly temperatures, radiation and rainfall; and (iii) hourly temperatures, radiation, wind speed and rainfall. The testing of HAYDMO revealed a satisfactory agreement between predicted and observed moisture contents.

1 INTRODUCTION

The conservation of hay in southern Australia is difficult because it is performed in a period of changeable weather. A simulation model has therefore been developed at the University of Melbourne to analyse haymaking systems and management techniques, with the objective of minimizing weather damage and maximizing the feed value of hay.

The main simulation is based on a series of sub-models associated with pasture growth, weather forecast, management, hay drying and hay losses. In this paper, the hay drying sub-model and the experiments on which it was based are described and the results presented.

The time required to reduce the moisture of freshly cut crop to a value suitable for storage depends on meteorological factors, crop factors and management factors. These factors, particularly the meteorological ones, are normally highly variable during the field drying, a fact which results in a large variation of drying time. Therefore, the modelling of the drying process is important in analysing haymaking systems.

There have been different approaches in the past 15 years or so to develop mathematical models expressing relationships between drying rate and various factors. The thin layer drying theory has been used to develop hay drying models based on laboratory studies (Kemp et al., 1972; Hill et al., 1977), but these are not capable of predicting the actual field-drying time, mainly because the effect of rain and dew, which are known to retard the drying of hay, is not considered.

Realizing the limitations of these models, Savole (1982) performed field experiments with alfalfa and developed a relationship between drying rate and a number of factors such as temperature, radiation, yield and mechanical treatments. The wind speed was found to be a non-significant factor. He also proposed simple models for rain and dew adsorption during the field drying process. The relative humidity, one of the important meteorological factors, affecting the drying was not considered as a factor affecting the drying rate. The model also has the limitation that it can be used only in areas where radiation data are available.

Bruck and Van Elderen (1969) and Thompson (1981) used a "combination" method of evaporation (Penman, 1948) to develop hay drying models. The major limitation of using Penman's approach is that it requires radiation data, which are not available from all meteorological stations.

Regression analysis has been widely used in developing the hay drying models (Hart and Burton, 1967; Spatz et al., 1970; Hayhoe and Jackson, 1974; Hill, 1976; Kemp et al., 1977; Oyer and Brown, 1977). However, the models developed so far have not adequately considered the effect of rain and dew.

Most of these models also cannot estimate the moisture content at any time during a day - a desirable feature from the standpoint of analysing haymaking systems more realistically.

The following guidelines were used in the development of the drying model HAYDMO (HAY Drying Model):

(i) The model should be able to predict drying time for unconditioned as well as conditioned hay.
(ii) The model should take into account the effect of rain and dew.
(iii) The model should be able to predict the moisture content at any time during a day.
(iv) The model should be able to operate with different meteorological parameters such as temperatures, wind speed and radiation.

2 HAY DRYING EXPERIMENTS

Field drying experiments were carried out during the haymaking season in 1983 at the Animal Research Institute in Werribee, Victoria. Twenty-four experiments, 12 each for unconditioned and conditioned treatments, were conducted with a perennial pasture comprised mainly of white clover (Trifolium repens L.) and perennial ryegrass (Lolium perenne L.).

Experimental procedures and hay drying curves are described in the following sections.

2.1 Experimental Procedures

2.1.1 Preparation of samples

Generally, on each day at 9 h, two swaths of pasture
were cut with a New Holland sickle bar mower. On some occasions, cutting was also done in the afternoon, at 13 h. In order to have samples with different moisture contents drying under the same environmental conditions. Soon after cutting, one of the swaths was conditioned, using a New Holland crusher.

Immediately after the conditioning operation, six samples, three each from unconditioned and conditioned pasture, were placed in rectangular trays. Each tray measured 1025 mm x 425 mm x 75 mm and was made of welded wire mesh, having square holes of 25 mm x 25 mm. The technique used in placing the sample was as follows. The empty tray was placed across the swath and the hay around its perimeter was cut with hand shears. The sample area under the tray was then lifted by means of two specifically constructed multi-pronged forks and placed in the tray, with as little disturbance as possible. The tray and sample were then placed back in the swath.

2.1.2 Moisture determination

The trays were weighed at one hour intervals for the first four hours of drying on the day of cutting, and then at 2-3 hour intervals till 20 h. On the subsequent days, the weighing of trays began at 6 h. If rain occurred during drying, the trays were weighed after the rain for the purpose of determining the increase in moisture due to the rain. The trays were weighed using an Avery semi-self-indicating weighing balance fitted with a special frame to hold the trays. The weighing was done in a temporary shed to avoid the effect of wind.

Towards the end of the drying period, a raking operation was simulated by inversion of the sample. For this purpose, an empty tray was placed over the top of a tray with a sample and the pair quickly inverted. The second tray was then placed back to the original position in the swath. The samples were weighed just before the raking operation and measurements were continued till the end of drying.

At the end of the drying cycle, the material from each tray was put into paper bags and then transferred to the laboratory for dry matter determinations using the oven method (Greenhill, 1960). Moisture content at each observation time was then calculated from the dry matter weight and the weights of the samples which had been taken during the field-drying process.

2.1.3 Recording weather data

An automatic portable weather station developed and described by Watts (1983) was set up near the test field to record meteorological parameters. The data collected were:

1. dry bulb temperature
2. wet bulb temperature
3. wind speed
4. global radiation.

Dry and wet bulb temperatures were recorded using a Bowen ratio system. This system measures the temperatures at two heights (1 m and 2 m) alternatively every 15 minutes. The average of these values was taken as a temperature reading at every half hour. A cup anemometer was used to record the wind run and global radiation was recorded using a pyrometer. A data logger continuously integrated the outputs from each sensor and punched the data onto paper-tape at 15 minute intervals.

Some meteorological parameters were recorded manually during the experimental period, with a view to using them if the automatic weather station failed to give reliable data. Dry and wet bulb temperatures were noted down every hour during the day (6 h to 20 h) using dry and wet bulb thermometers placed in a Stevenson screen near the site. Minimum and maximum temperatures were also recorded for each day during the experimental period. A standard rain gauge was installed in the field to measure the rainfall.

2.2 Drying Curves

Drying curves were plotted from the data of all the 24 experiments. As an example, the curves for two experiments are presented (Fig. 1) to show how the moisture content of unconditioned and conditioned hay changed in the field conditions. The weather data taken during the two experiments are also shown in this figure.

![Figure 1 Drying curves for unconditioned and conditioned hay](image)

During the first 3-4 hours of drying, plant moisture is lost very rapidly. By noting the general slopes of the drying curves and by inspecting minimum daily moisture contents, it is clear that the conditioned hay dried more rapidly than the unconditioned hay. Fig. 1 suggests that under favourable weather conditions it would have been possible to bale the conditioned hay on the day after cutting. Unconditioned hay would have normally required an extra day before it could be baled.

The moisture uptake during the night was largely dependent upon the weather conditions during that
Any given hour during the day could be either rain-free or rainy. Thus, there is a need to develop the relationship for CMₜ,₁ for both cases.

The drying crop may have either original plant water or that absorbed due to watering after rain or dew. Therefore, the drying data was separated into these two main categories and two sets of equations were developed to estimate CMₜ,₁ during a rain-free hour. The effect of several factors on change in moisture content was investigated. These factors were:

(i) moisture content at the beginning of the hour;
(ii) vapour pressure deficit during the hour;
(iii) wind speed during the hour;
(iv) global radiation during the hour;
(v) yield of pasture;
(vi) conditioning factor distinguishing between conditioned and unconditioned hay;
(vii) raking factor distinguishing between raked and unraided hay.

A variety of linear and curvilinear functions were investigated as potential forms for empirical relationships between CMₜ,₁ and the above factors. Multiplicative power functions of the following type were found to give the best fit to the data:

\[ y = a_0 \prod_{k=1}^{n} x_k^a_k \]  

A number of equations were developed for the estimation of CMₜ,₁ by using different combinations of weather variables. Table II (equations 6–8) and Table III (equations 9–10) give the results of multiple regression analysis for original plant water and rain/dew water respectively. The description of the symbols used for independent variables is as follows:

- Mᵢ,₁ = moisture content at the end of i-th hour
- MVPDᵢ,₁ = mean vapour pressure deficit during i-th hour
- Wᵢ,₁ = wind speed during i-th hour
- RGᵢ,₁ = global radiation during i-th hour
- CONDᵢ,₁ = conditioning dummy variable
- RKᵢ,₁ = raking dummy variable

The drying rate (CMᵢ,₁) was significantly affected by all but one factor, viz. the yield of pasture. This was in apparent contradiction of the results obtained by Hart and Burton (1967), who found that moisture content at the end of the day was significantly affected by the yield of crop. However, the experiments performed by them covered a large range of yield (0.43–13.82 t ha⁻¹) which would have contributed towards its significance in the drying equation. The present study has investigated the yield range of only 3.4–6.0 t ha⁻¹.

Of all the weather variables, the contribution of wind speed in predicting the drying rate was relatively low. When included, the increase in R² and decrease in SE values were very small, as is evident from the comparison of their values for equations 7 and 8. The wind speed was also found to be a non-significant variable when the hay contained rain or dew water (Table III).

The analysis suggests that the drying rate, I moisture content per hour, of conditioned hay was about 40% higher than that of the unconditioned hay when the crop contained original plant water only. This

### Table II

<table>
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<td>0.91</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

R² = coefficient of determination  
SE = standard error of estimate  
N = number of observations

### Table III

<table>
<thead>
<tr>
<th>Eqn</th>
<th>Variable</th>
<th>Coeff.</th>
<th>Constant</th>
<th>R²</th>
<th>SE</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>Mᵢ,₁,₁-1</td>
<td>1.14</td>
<td>-0.0529</td>
<td>0.76</td>
<td>9.5</td>
<td>131</td>
</tr>
<tr>
<td></td>
<td>MVPDᵢ,₁</td>
<td>0.27</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(1+COND)</td>
<td>0.28</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Mᵢ,₁,₁-1</td>
<td>1.02</td>
<td>-0.0767</td>
<td>0.83</td>
<td>7.9</td>
<td>131</td>
</tr>
<tr>
<td></td>
<td>RGᵢ,₁</td>
<td>0.38</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(1+COND)</td>
<td>0.22</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The drying rate was also significantly affected by the yield of the crop. When included, the increase in R² and decrease in SE values were very small, as is evident from the comparison of their values for equations 7 and 8. The wind speed was also found to be a non-significant variable when the hay contained rain or dew water (Table III).

The analysis suggests that the drying rate, I moisture content per hour, of conditioned hay was about 40% higher than that of the unconditioned hay when the crop contained original plant water only. This
moisture content does not increase at the same rate for unconditioned and conditioned hay as the amount of rainfall increases. The model also suggests if there is a continuous rainfall of more than one hour, then the rainfall during that period should be accumulated and the change in moisture content for the whole period should be calculated, using equation 11.

3.3.2 Estimation of change of moisture content during the night

Any given night (sunset to sunrise) during the field-drying process could be either rainy or rain-free. Hence, two separate equations are also needed to predict the change in moisture content.

The effects of the following factors on change in moisture content during a rain-free night were investigated:
(i) moisture content at the end of the day;
(ii) average vapour pressure deficit during the night;
(iii) average wind speed during the night;
(iv) yield of pasture;
(v) conditioning factor distinguishing between conditioned and unconditioned hay.

A number of relationships were tried and linear equations of the following type were found to give the best fit to the data:

\[ y = a_0 + \sum_{k=1}^{n} a_k x_k \]  

(12)

Table IV (equations 13 and 14) gives the results of multiple regression analysis of change in moisture content during the \(i\)th night (\(CMN_i\)) with various independent variables. The description of the symbols used is as follows:
\(\text{ME}_i\) = moisture content at the end of \(i\)th day after cutting, \(t\) dry basis;
\(\text{VPDN}_i\) = average hourly vapour pressure deficit during the \(i\)th night after cutting, kPa;
\(Y\) = yield (dry matter) of pasture, t ha\(^{-1}\).

<table>
<thead>
<tr>
<th>Eqn</th>
<th>Variable</th>
<th>Regrn Coeff.</th>
<th>Constant</th>
<th>(R^2)</th>
<th>SE</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>(\text{ME}_1)</td>
<td>-0.15</td>
<td>68.7</td>
<td>0.79</td>
<td>9.4</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>(\text{VPDN}_1)</td>
<td>-81.73</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>(\text{ME}_1)</td>
<td>-0.14</td>
<td>107.8</td>
<td>0.85</td>
<td>7.9</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>(\text{VPDN}_1)</td>
<td>-83.58</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Y)</td>
<td>-8.47</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The model suggests that moisture content during a rain-free night could also decrease if the moisture content at the beginning of night and/or vapour pressure deficit during the night are sufficiently high. Swaths having higher yields would result in a smaller increase in moisture content compared to the swaths having lower yields. This was also evident during the experiments, where it was found that only the upper layers absorbed the moisture resulting in overall less increase in moisture content of swaths having greater thickness. No significant difference was found between conditioned and unconditioned hay. Wind speed was also found to be a non-significant variable.

For a rainy night, equation 15 can be used to predict the increase in moisture content due to rainfall. This equation is essentially the same as equation 11, but \(Rd_{ij}\) is replaced by \(RN_{ij}\).

\[ CMN_{ij} = 131.8 \text{RN}_{ij}^{3.19 \ast (1-COND)}^{2.27} \]  

(15)

where \(RN_{ij}\) = rainfall during the \(i\)th night after cutting, mm.

4 DEVELOPMENT OF A COMPUTER PROGRAM HAYDMO

A computer program HAYDMO (HAY Drying Model) was written in FORTRAN 77 to simulate the moisture content of hay after cutting. The program logic is shown in Fig. 2 and a listing is available from the authors, on request. The weather input data required are given below:
(i) hourly mean vapour pressure deficit, kPa (6 h to 20 h);
(ii) hourly wind speed, m \(s^{-1}\) (6 h to 20 h);
(iii) hourly global radiation, MJ m\(^{-2}\) (6 h to 20 h);
(iv) hourly rainfall, mm (6 h to 20 h);
(v) average hourly vapour pressure deficit during the night, kPa (20 h to 6 h);
(vi) rainfall during the night, mm (20 h to 6 h).

![Figure 2 Flow chart of the hay drying model (HAYDMO)](https://example.com/flowchart.jpg)

The model can be operated without data items (ii) and (iii) by selecting appropriate drying equations from Tables II and III. Hence, the estimation of drying time is also possible in those areas where radiation data are not available.

5 TESTING OF HAYDMO

The drying data of 22 experiments were used to develop the regression equations described in Section 3. The remaining data of two experiments were used to
test the performance of the model. The computer program HAYMOD was used to simulate the drying process using these experiments. Figs. 3 and 4 show the predicted drying curves and the observed data for these experiments.

The comparison of observed and predicted moisture contents reveals that the model is able to simulate the sawtoothed types of drying curves normally expected during field-drying of hay. The model shows good sensitivity to both the type of hay and the change in drying conditions. The comparison of predicted and observed moisture contents at the point of maximum rewetting suggests that the increase in moisture content due to rain is predicted quite satisfactorily by equation 11.

![Figure 3 Predicted and observed moisture contents of unconditioned hay](image)

In general, there is close agreement between the observed and predicted moisture contents. The model appears to predict the moisture contents more accurately during the early periods of drying compared to the later periods. The reason could be that fewer data in the lower moisture content range were available which could have caused the model to be less accurate in predicting the moisture content in that range. Also, some errors could have arisen due to the inability of the weighing system to record the small changes in weight which occur during the later periods of drying. However, the model seems to be sufficiently accurate for use in studies relating to decision making models such as simulation of haymaking systems.

6 CONCLUSIONS

The hay drying model developed can adequately simulate the drying and rewetting processes occurring during field-drying of hay. A non-linear model is used to relate the drying rate during daytime to weather and management factors. The hay which has been wet dries differently from hay which has not and hence two sets of equations are developed, one for the hay having original plant water only and the other for the hay having rain/dew water also. Statistical analysis of the drying data reveals that the drying rate is mainly a function of moisture content of the hay, vapour pressure deficit, global radiation and machinery treatments. The effect of wind speed is small compared to other meteorological factors. Some past studies have found that the drying rate is affected by yield of hay, but in this work, the effect of the small yield range on drying rate has been found non-significant. Two simple models are also developed to simulate the rewetting process of hay, either due to rain or dew.

The drying model is being used for the development of a haymaking simulation model to analyse haymaking systems and management techniques, with the objective of minimizing weather damage and maximizing feed value of hay.

7 ACKNOWLEDGEMENTS

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