A LINEAR PROGRAMMING STUDY OF THE EFFECTS OF CLIMATIC CHANGE ON SCOTTISH AGRICULTURE.

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DECLARATION.

I hereby declare that this thesis has been composed by me, and all the work presented is my own unless stated otherwise.

April, 1998

April, 1998 John David Finlayson.

ABSTRACT.

Although there is considerable uncertainty in the literature about the effects of greenhouse gases on the climate there is little doubt that the composition of the atmosphere has changed in recent times. As a result of human activities the concentration of CO_2 is likely to double from pre-industrial levels by the middle of next century and as a consequence global temperatures are likely to rise. The potential importance of a change in the climate for the environment and agriculture and the complexity of the issues that are involved means that it is important to develop analytical tools to study this problem. The principle aim of the study is to evaluate the possible effects of a change in climate on the pattern, structure and viability of agriculture in Scotland. To address this objective it was necessary to evaluate the effects of climate change at a range of different levels of resolution.

A linear programming model was developed that includes a large amount of biological, physical and economic detail. The models of crop growth (grass, grass /clover, swedes, potatoes, barley, vining peas, oilseed rape and wheat) account for variations in weather conditions, soil types, weeds, applications of nitrogen and pesticides, different planting dates and cropping rotations. The livestock operations that are modelled include sheep, dairy and beef fattening enterprises. In addition a considerable amount of effort was devoted to modelling variations in machinery requirements (and the sensitivity of these operations to climate), labour, buildings and finance. The inclusion of this information has allowed the types of adjustments that farmers may implement to be considered.

The model is structured as a series of linked sub-problems where the most basic units are farms. In turn the interactions between farmers in terms of flows of intermediate goods, land, and labour are considered at the regional and national level. While further developments to the model would allow the status of Scottish agriculture to be more accurately modelled, in its current stage of development, the model has allowed a realistic evaluation of the effects of climate change. The results of this study suggest that climate change will have a detrimental effect on Scottish agriculture, however, the effects of climate are likely to vary between the different farm types and regions. In general, cropping farms are likely to benefit from a change in climate while the profitability of livestock farms, and sheep in particular, will decline.

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LIST OF ABBREVIATIONS.

Abbreviation	Definition
AWC	Available Water holding Capacity
CAP	Common Agricultural Policy
DM	Dry matter
D-W	Dantzig-Wolfe
EPCC	Edinburgh Parallel Computing Centre
ERGOL	Edinburgh Research Group Optimisation Library
ESCA	East of Scotland College of Agriculture (Now known as Scottish Agrigultural College, Edinburgh)
EU	European Union
FAS	Farm Accounts Scheme
FYM	Farm Yard Manure
GAI	Green leaf area index
GIS	Geographic Information Systems
IBM	International Business Machines
IPCC	Intergovernmental Panel on Climate Change
LFA	Less Favoured Area
LP	Linear Programming
MILP	Mixed Integer Linear Programming
MOG	Material other than grain
MOTAD	Minimisation of Total Absolute Deviation.
OSL	Optimisation Subroutine Library
RHS	Right hand side coefficients of matrix
SAC	Scottish Agricultural College.
SOAEFD	Scottish Office, Agriculture, Environment and Fisheries Department

LIST OF VARIABLES.

Variable	Definition	Equation
z	Objective function of linear programming problem.	4-1
c	Cost vector.	4-1
x	Solution vector.	4-1
A	Coefficient matrix.	4-2
b	Right hand side coefficients.	4-2
R	Number of sub-problems.	4-4
B	Coefficient matrix associated with sub-problem.	4-6
Γ	Arable crop yield (kg DM)	5-1
μ	Potential increment in harvestable crop yield (kg DM)	5-1
η	Soil nitrogen (kg)	5-1
a1	Nitrogen taken up per unit of harvestable crop yield (kg kg^{-1})	5-1
c	Crop type	5-1
t	Integration step (months)	5-1

Variable	Definition	Equation
ω	Amount of weed material present in the crop (kg DM)	5-2
a2	Basal limit to the potential yield increment (kg DM)	5-2
a3	Contribution to the potential yield of a crop per unit of pesticide	5-2
a4	Reduction in potential crop yield associated with competition between weeds and the growing crop for light and moisture	5-2
m	Type of pest control measure	5-2
P	Amount of fungicide and insecticide applied to a crop (kg active ingredient)	5-2
a5	Losses associated with death and decay (kg kg^{-1})	5-3
FH	Mechanical harvesting of forage (kg DM)	5-3
I	Animal intake (kg DM)	5-3
K	Amount of leaf material present in the field (kg DM)	5-3
ω	Weed material (kg DM)	5-4
$\Delta\omega$	Growth of weed matter (kg DM)	5-4
$c\omega$	Death and decay of weed matter associated with pesticide measure (kg DM)	5-4
a6	Potential growth limit associated with weed seed and root reserves (kg DM)	5-5
a7	Increment to potential weed growth per kilogram of weed matter (kg DM kg DM^{-1})	5-5
$s\omega$	Unfulfilled potential weed growth (kg DM)	5-5
a8	Amount of weed material that dies per unit of active ingredient contained in a herbicide	5-6
H	Amount of herbicide applied to a crop (kg active ingrediant)	5-6
ϑ	Vector of 0 / 1 integer variables	5-7
W	W is an arbitrarily large coefficient	5-7
φ	Allows weed growth to occur at less than potential rates	5-8
a9	Machine work rate	5-11
h	Month of harvest	5-11
M	Hours worked by a machine (hours)	5-11
S	Straw (kg DM)	5-11
a10	Basal requirement to dry grain (hours kg DM^{-1})	5-12
a11	Increment in drying associated with weeds (hours kg DM^{-1})	5-12
a12	Number of spray applications that can be applied to a crop	5-13
a13	Amount of active ingredient that can be applied per application (kg $hectare^{-1}$)	5-13
$\omega\eta$	Effect of growing weeds on nitrogen (kg)	5-14
f	Fertilizer nitrogen applied to soil (kg)	5-14
a14	Proportion of soil nitrogen that is lost from the preceding period	5-14
a15	Available nitrogen content of farm yard manure (kg kg^{-1})	5-14
a16	Nitrogen excreted by animals (kg kg DM^{-1})	5-14
$c\eta$	Effect of growing crop on nitrogen (kg)	5-14

Variable	Definition	Equation
a17	Uptake of nitrogen by growing weeds (kg kg^{-1})	5-15
a18	Nitrogen leached from dead weed material (kg kg^{-1})	5-15
$\gamma\eta$	Nitrogen derived from miscellaneous sources (kg)	5-16
a19	Nitrogen derived from dead plant material (kg kg^{-1})	
a20	Nitrogen fixed by a crop (kg)	5-17
a21	Atmospheric deposition of nitrogen (kg)	5-17
a22	Net mineralisation (kg)	5-17
a23	Nitrogen that is transferred from the preceding crop (kg)	5-17
a24	Nitrogen that is transferred from crops planted two years previously (kg)	5-17
d	Method of residue disposal	5-17
Λ	Relative soil mineralisation rate	5-18
T	Temperature (°Kelvin)	5-18
Ta	Mean annual temperature of region (°Kelvin)	5-18
%N	Percentage of the dry weight of a crop that is nitrogen	5-19
W	Total plant dry weight (tonnes hectare^{-1})	5-19
ΔLW	Change in liveweight (kg head^{-1})	6-1
j	Animal liveweight category	6-1
LW	Animal liveweight (kg head^{-1})	6-1
N	Animal number	6-1
N_P	Number of animals purchased	6-1
N_S	Number of animals sold	6-1
a25	Proportion of metabolisable energy intake allocated to animal growth	6-3
a26	Energy content of liveweight (MJME kg^{-1})	6-3
k	Energy intake is classified as being either less than (k = 1) or greater than maintenance plus pregnancy requirements (k = 2)	6-3
kf	Efficiency of utilisation of metabolisable energy for liveweight growth	6-3
LW_L	Liveweight loss that would occur if animal is fasted (kg head^{-1})	6-3
MEI	Energy intake of an animal (MJME head^{-1})	6-3
Emaint	Metabolisable energy required to maintain an animal (MJME)	6-4
Epreg	Metabolisable energy requirement of gestation (MJME)	6-4
PMEI	Potential energy intake of an animal (MJME head^{-1})	6-6
a27	Metabolisable energy content of a feed (MJME kg DM^{-1})	6-7
p	Feed type	6-7
a28	Maximum intake of indigestible feed (kg IDOM. kg LW^{-1}.head^{-1})	6-8
a29	Indigestible organic dry matter content of a feed (kg IDOM. kg DM^{-1}).	6-8
a30	Minimum pasture cover that must be maintained in the field (kg DM ha^{-1})	6-9

Variable	Definition	Equation
C	Amount of land planted to a crop (hectares)	6-9
a31	Energy content of milk (MJME. litre^{-1})	6-10
kl	Efficiency of utilisation of metabolisable energy for lactation	6-10
L	Milk production (litres)	6-10

1. INTRODUCTION.

Although there is a great deal of uncertainty in the literature about the effects of greenhouse gases on the climate (Barbier and Pearce, 1990; Henderson-Sellers, 1991; Kellog and Schware, 1981; Parry, 1990a; Rosenzweig, 1989b; Smith and Tirpak, 1989) there is little doubt that the atmosphere has changed as a result of human activities. The Intergovernmental Panel of Climate Change (IPCC) (1990, 1996a and 1996b) have suggested that the concentration of CO_2 is likely to double from pre-industrial levels by the middle of next century and as a result, global temperatures are likely to increase. However, the predictions of the extent and the rapidity of temperature rises are subject to a wide degree of variation. While many of the physical processes that govern weather are reasonably well understood, there are still large gaps in understanding how these processes will affect global and regional weather patterns (Rowntree *et al.*, 1989).

However, the potential costs to society and also the evidence for climate change are sufficiently high that climatic change has become the subject of intense political activity and study. For example, the Conference of the Parties that was held in Kyoto from December 1-12, 1997, is merely the latest in a series of conventions that have been convened to negotiate legally binding agreements between nations to reduce greenhouse gas emissions. There has also been a large international response to facilitate research and transfer information between governments. The IPCC, which was established in 1978, has played a significant and ongoing role in this process.

Although, in recent decades, there has been a fundamental shift in societal attitudes towards preserving and maintaining the global environment there are still considerable difficulties involved in the negotiation and implementation of the treaties that relate to climate change. Not least of these difficulties is related to the differential impact that changes in climate will have in different parts of the world. Also, there is disagreement as to the level of financial responsibility of the developed world to ensure that developing countries adopt technologies and policies that are of global benefit. Issues such as these have complicated the arguments at Kyoto, as well as previous international conventions[1], and impeded the setting of enforceable targets for emissions of greenhouse gases. However, the disagreements at Kyoto relate to topics such as how deep the cuts in emissions should be and the dates for achieving these

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[1] Such as the 1992 UN Framework Convention on Climate Change in Rio de Janeiro which was signed by 154 states and the European Union.

targets. The more basic argument as to whether limits on the emissions of greenhouse gases are required is now no longer an issue.

The significance of climate change for the environment (Boer and De Groot, 1990; Bolin *et al*, 1986; Glantz, 1991; Grime, 1990; Jackson *et al*, 1990; McNeely, 1990; Risch, 1987) and agriculture (Adams, 1989; Carter *et al*, 1990; Crosson, 1989; Kates *et al*, 1985; Parry *et al*, 1988a and 1988b; Rosenzweig, 1989a; Salinger *et al*, 1990) and the complexity of the issues that are involved means that it is important that the debate and the decisions of policy makers, at local through to the international level, are made on an informed basis. In the context of this study it is perhaps less important to become involved in the debate as to how the climate will change than to be able to incorporate projected changes in weather patterns within a methodology that allows the resulting impacts to be quantified in a reasonably objective and comprehensive manner.

The primary objective of this research is to consider the effects of climate change on the pattern, structure and viability of agriculture in Scotland. Because of the complex nature of this problem it was necessary to adopt mathematical modelling as the tool of analysis. Further, as farmer's responses, either to mitigate the detrimental effects or to take advantage of beneficial aspects of climatic change, are likely to influence the outcomes associated with climate change it was desirable to use an optimising technique that can be used to approximate the responses of producers.

Of the optimising techniques that are available, notably linear[2], quadratic, dynamic, and mixed integer modelling, linear programming was chosen, as it is a relatively simple technique. Further, the methods used to solve linear programming (LP) models are well developed and can be applied to large problems. Other advantages and strengths and weaknesses of linear programming versus other techniques are reviewed by Dent et al., (1986) and Romero and Rehman (1989). Although, econometric methods are a commonly used technique, and possess certain advantages over the previously listed methods (such as the ability to extract a large amount of information from sample data and provide an indication of the statistical reliability of the results), this technique was not used in this study. The reason for this is that econometric models are not well suited to situations where production conditions are

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[2] Techniques that are derived from LP such as Goal Programming and Minimisation Of Total Absolute Deviation might also have been considered.

likely to move away from the historically observed sample on which the model was estimated (Moxey *et al*, 1995; Shumway and Chang, 1977).

The implications of the study objective for the model structure, and also some of the conceptual and data-related issues that are involved in constructing the model are discussed in the following section. In Section 1.2 of this chapter an outline of the thesis is presented.

1.1 Methodological Considerations.

Perhaps the most significant methodological difficulty that climatic change presents is that the effects of climatic change occur over an extremely wide range of temporal and spatial scales. In some cases, physical and biological responses to a change in climate may occur very rapidly, particularly if a direct relationship exists between weather and the response; such as rainfall affecting daily rates of crop growth. At the other extreme, effects may be the result of interacting or slowly responding processes so that the response is fully manifested only after a long period of time; an example might be the influence of a change in climate on the properties of a soil. The effects of climatic change on processes occurring at different scales of spatial consideration are also significant. For example, processes occurring at very small or even microscopic levels, such as soil organisms, pests and diseases, are affected by climate. At a larger scale, a change in climate may have differential impacts on the agricultural potential of a country, depending on the weather patterns that evolve in different regions.

The responses in consumption and production to climatic change are no less varied than the biological and physical consequences in terms of the scale of temporal and spatial impacts on economic behaviour (Sonka, 1991). Farmers modify their management to take advantage of beneficial changes in climate or to reduce the detrimental effects of an adverse shift in climate. The actions taken by farmers may range from relatively minor adjustments, such as advancing or delaying the timing of field operations, that have little effect on farm output, to fundamental and long-term changes in management that alter the farming system. These adjustments in turn have implications for the welfare and location of other producers, processors and consumers in the agricultural sector. Further, the impacts of a change in climate are likely to be complicated by changes in factors such as legislation and institutional structures.

Johnson (1991) reviewed the relative strengths of a range of differing economic modelling approaches to contend with methodological difficulties common to studies of climatic change. He also analysed the types of assumptions and information that are required and produced by models constructed at differing levels of aggregation. Typically, models that predict the behaviour of producers, which Johnson calls individual decision models, model short-term changes in system behaviour. Models of this type are capable of producing a wealth of information about dynamic adjustments at the farm level but they can be extremely demanding in terms of data requirements. The amount of detail in these models means that they frequently incorporate highly structured assumptions about producer attitudes to risk. At the same time, factors such as technological change and prices of agricultural inputs and outputs are often assumed to be constant. The use of simplifying assumptions such as these, means that the results of analyses may over-state the impact of climatic change on farming systems (Johnson, 1991).

Compared with micro-economic models, models constructed at higher levels of aggregation tend to adopt less restrictive assumptions towards factors that vary over the longer term or that are the result of market interactions. Aggregate models, therefore, tend to be suited to studies that explicitly consider events that occur outwith a farm's boundary. Conversely, in micro-economic level studies, perturbations that occur beyond a farm's boundary are assumed to influence the environment in which a farm operates, but interactions between the farm and its environment are not normally considered. As models become more aggregated this is often reflected in the adoption of increasingly simplified assumptions regarding farming practices and decisions. The use of such assumptions means that model construction and evaluation tend to be more tractable, however, this can be at the cost of a greater incidence of aggregation bias.

A further point is that the production functions that underlie higher order models tend to be specific to the range of historical data used to estimate the model parameters. When it is considered that analyses of climatic change may be performed for situations where the environment is quite different to that existing today, the relationships included in aggregate models often lack the generality required to produce acceptable predictions of the impacts of climatic change on agricultural production. Insofar as a micro-economic model explicitly represents causal biological and economic relationships, these are likely to have fewer problems than an aggregate model when extrapolating explanatory variables beyond the range of past experience (Buckwell and Hazell, 1972).

The complexity of the biological and physical processes that link crop and animal production to weather variables means that simulation models are essential for generating predictions of the effects of variations in climate (Baier, 1977; van Keulen, 1987; Wisiol, 1987). In the past, simulation studies have often used statistical techniques to estimate empirical responses in crop or animal performance to comparatively small sets of variables. While the outputs of these studies are usually acceptable for analyses involving a restricted set of locations and recorded conditions large errors can occur when considering other locations or conditions outwith the measured range.

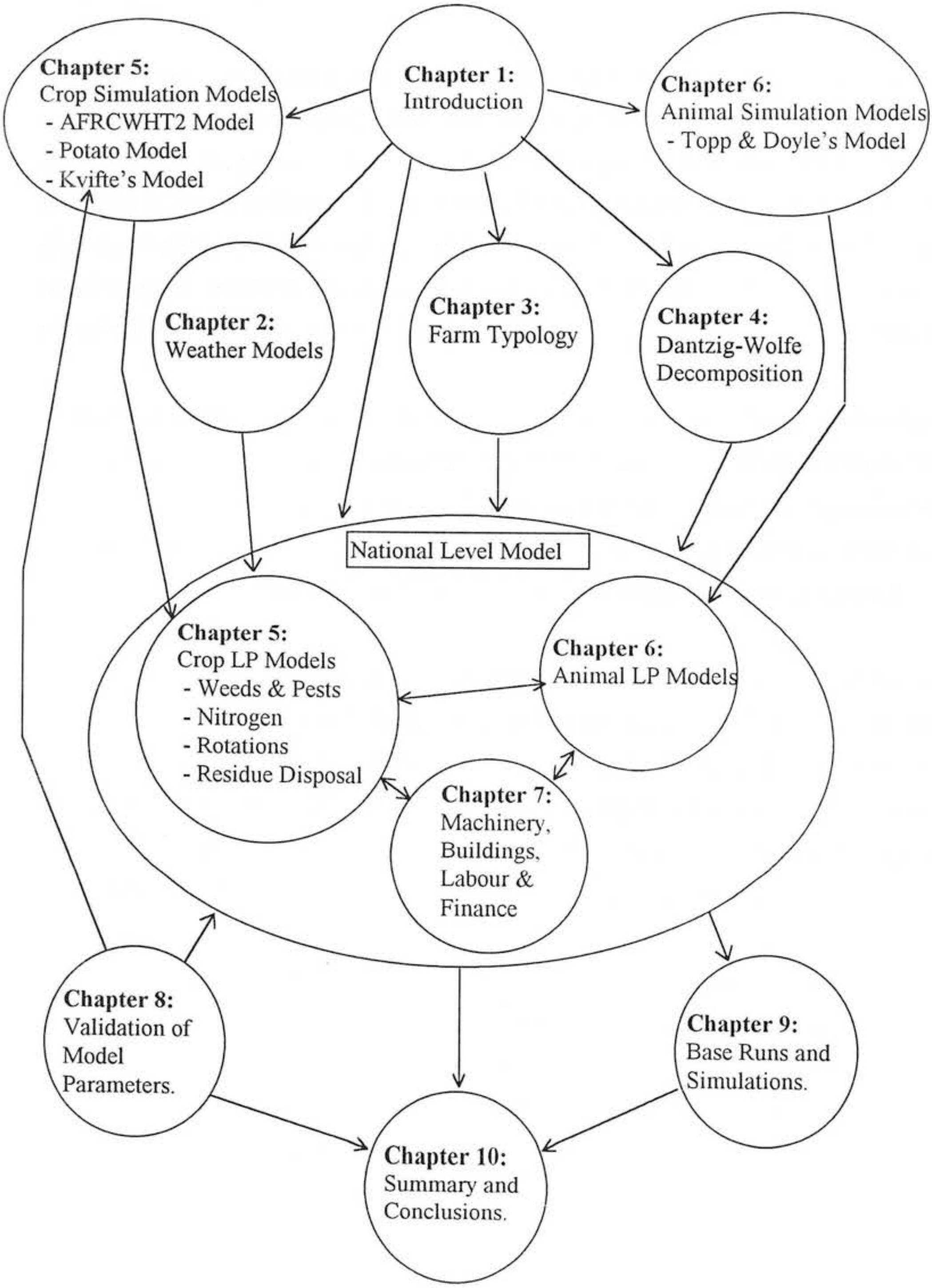
As knowledge of the workings of biological systems have improved, and sufficiently accurate and detailed data are collected, simulation models have increasingly included mechanistic, or biologically meaningful, representations of the processes involved in crop and animal growth and development. The principle advantage of mechanistic models is that they tend to be more robust than empirical models when considering a range of locations and conditions, an important requirement in this study. To the extent that the national level model summarises output from simulation models, any errors and uncertainties present in the simulation models are also embodied in the higher-order model.

As the following chapters will show a sophisticated LP model was established as part of this thesis. Specifically, a hierarchy of sub-models was developed where output is provided by a national level model. The national model is comprised of a series of regional sub-models which are themselves comprised of a set of farm sub-models. In turn the farm sub-models contain a series of enterprise sub-models.

1.2 Thesis Outline.

This chapter has provided a brief introduction to the study. In the first section, the primary objective of the study, that is to consider the effects of climate change on the pattern, structure and viability of agriculture in Scotland, is introduced. Also, some of the difficulties involved in establishing international agreements on issues that relate to climate change are considered. Further, some of the methodological considerations that are associated with using mathematical and simulation models as the tools of analysis are discussed. In the remainder of this section the structure of the thesis is presented (see Figure 1-1).

Figure 1-1. Thesis Structure.



As mentioned above, the model incorporates a series of regional sub-models, where each of the regions correspond to a weather zone. The weather zones, that are included in the model, define the spatial dimensions (Aspinall *et al*, 1994b) of the synthetic weather series (Peiris and McNicol, 1996; Peiris *et al*, 1996) that are used to estimate changes in productivity with changes in climate at different locations in Scotland. The model that is used to establish the weather series for the regions that are included in the model is described in Chapter 2. Also, included in Chapter 2 is a summary of the outputs of the weather model.

In Chapter 3 the results of a cluster analysis that provides the basis for the farm type sub-models is presented. The farm typology analysis was necessary to establish an accurate description of the asset structure and production possibilities that are available to Scottish farms. The rationale for establishing the typology, the principle sources of data, the methodology, and the variables that are included in the analysis are discussed. Some of the issues that are associated with aggregation bias are also presented. The results of the typology are included in the final section of the chapter.

Because of the large size of the linear programming model that was developed in this study it was necessary to decompose the problem into a series of linked sub-models so that it could be solved. In Chapter 4 the rationale of the Dantzig-Wolfe decomposition technique is discussed. Also the outcome of efforts to solve the model on a parallel super computer and a network of Sun computers are presented.

The structure and limitations of the crop and forage models and the methods that are used to represent management variables are discussed in Chapter 5. Included in the chapter are sections that relate to the modelling of weeds and pests, nitrogen transformations within soils, crop rotations and crop residue disposal. The results of the estimation process that is used to establish the parameters in the LP model and the simulation models that provide inputs to this study are discussed.

Chapter 6 deals with the modelling of livestock. The models developed by Topp and Doyle (1994) act as a significant input to this part of the study. In the first section an overview of the farming systems that are modelled by Topp and Doyle is presented. In the second section, the equations and parameter estimates that describe animal performance are discussed. The formulation of the LP model is compared with

Topp and Doyle's model and some theoretical considerations are discussed. The final section of the chapter deals with the derivation of management parameters.

In Chapter 7 the structure of the machinery, buildings, labour and finance components of the model are considered. The availability of workable hours to complete machinery operations is highly weather dependent and is therefore considerably influenced by climatic change. The models developed by Cooper and McGechan (1994 and 1996) provide the principle source for estimating the parameters that relate to workable hours. The methods that are used to model variations in workable hours and the integration of these with machinery are discussed.

In Chapter 8 an evaluation of the model evaluation is presented. In the first part of the chapter the cash and forage crop models are considered. There are three parts to the evaluation of the crop models. Although most of the simulation models that provide inputs to this study have been extensively tested for British conditions, and were therefore adopted for use in this study without additional validation, one of the models was originally developed in Scandinavia by Kvifte (1987) and had to be modified as part of this study. It was important therefore to evaluate the predictive performance of Kvifte's model against Scottish trial data. The results of this comparison and conclusions relating to the suitability of using this model are presented in Section 8.2.1. In Sections 8.2.2 and 8.2.3 the ability, of the LP models of crop and pasture growth, to reproduce potential yield variations are discussed. In particular the influence of nitrogen on crop and pasture productivity is considered. In Section 8.3 the predictive performance of the animal models is examined. The outputs from the linear programming models of the animal production systems are compared with predictions produced by Topp and Doyle's models.

The results of the experiments that are performed with the model are discussed in Chapter 9. In the first section of this chapter the outputs of some preliminary runs with the model are considered. In Section 9.2 a sensitivity analysis of relative changes in the productivity of machine harvested crops (potatoes, barley, vining peas, oilseed rape and wheat) and crops harvested by animals (grass, grass / clover and swedes) is presented. These runs were performed to allow the sensitivity of livestock farming systems to be compared with systems that are dependent on the sale of crop produce. In the final section the constraints that relate to the purchase and selling of land and also the maximum numbers of livestock that can be carried are relaxed. The purpose of this experiment is to determine the longer term effects of climatic change on the relationships between farm types and regions. In the final chapter a summary of the study and the conclusions that have been reached is presented.

2. WEATHER.

2.1 Introduction.

This chapter is in three sections. The first section provides a brief description of the weather model that is used in this study. Some of the issues relating to the data generated by this model, and also the use of this data, are discussed. In the second section, the outputs of the weather model are presented for the range of climates and regions in Scotland that are considered in this study. In the final section, some conclusions are drawn regarding the relative changes in weather that may occur with a change in climate.

In this study the climatic scenarios that are considered include ten years of weather data, three possible climates and four regions in Scotland. The weather data that is used in this study, was established using a multivariate time series model developed by Peiris and McNicol (1996). The parameters in Peiris and McNicol's model were estimated from historical data that were specific to the sites that they selected as part of their study. The predictive performance of the weather model was assessed by Peiris and McNicol, and the results of their evaluation suggest that their model is adequate for the purposes of this study. Peiris and McNicol's model adopts a daily time step and outputs include wind speed, relative humidity, minimum and maximum temperature, radiation and rainfall. The output of their model is in the form of stochastic series that could be of any desired duration.

The climatic scenarios included in this study are: the current climate (climate '0'); a climate involving an increase in temperature of 3° Celsius and a concomitant change in mean rainfall[3] (climate '1'); and a climate where temperature increases by 3° Celsius but without a change in mean rainfall (climate '2'). The difference in average temperatures between climate '0' and climates '1' and '2', conform with estimates of temperature changes that may occur if the concentration of atmospheric carbon dioxide doubles from levels that existed in pre-industrial times (Parry, 1990b; Rowntree, 1990; Rowntree and Walker, 1978). In this study it is assumed that climate '1' is the most likely outcome associated with a doubling of atmospheric carbon dioxide. The climate '2' scenario is included in this study to assess the sensitivity of crop and forage production and machinery operations to variations in

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[3] For climate '1' rainfall is allowed to vary as a function of the change in temperature.

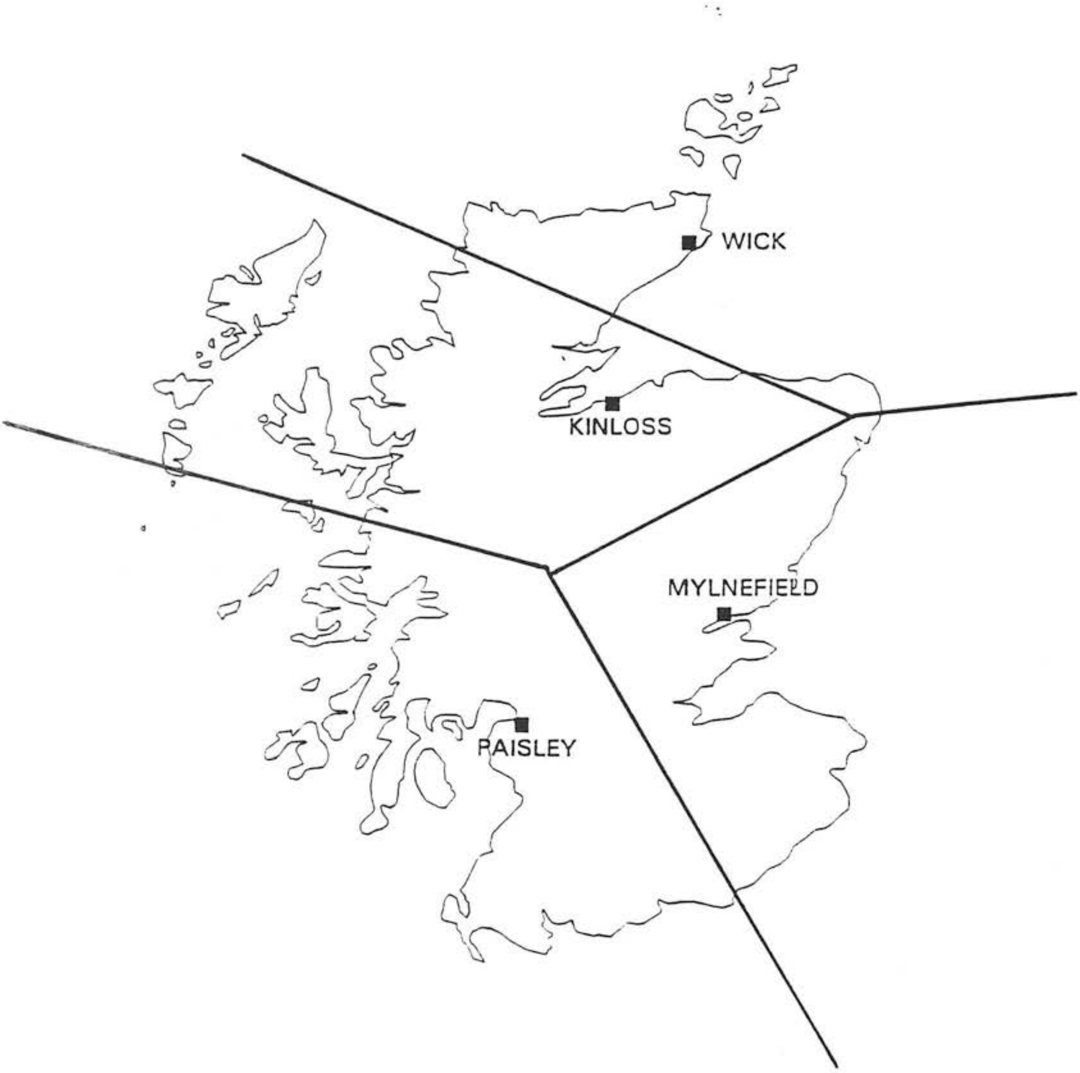
rainfall. For each of the above scenarios the monthly means of the variables produced by Peiris and McNicol's (1996) model are presented in Table 2-1 to Table 2-5.

The sites considered by Peiris and McNicol (1996) were Kinloss, Mylnefield, Paisley and Wick. Peiris and McNicol selected these sites, as relatively complete data sets of at least ten years duration were available. Also, they considered the sites to be representative of a relatively wide range of climatic categories that are of relevance to Scottish agriculture. In this study Scotland is sub-divided into four regions so that each region corresponds to one of Peiris and McNicol's sites. The boundaries of these regions are estimated by calculating equidistant points between Peiris and McNicol's sites (Aspinall *pers. comm.*, 1995; see Figure 2-1). An assumption of this procedure is that the weather series established by Peiris and McNicol's model provide reasonable estimates of conditions throughout the selected regions.

The assumption that the regions, or weather zones, possess homogenous weather conditions is, however, a simplification for two reasons. The first is that the number of regions that are represented in the model is small when the spatial diversity of Scottish weather is considered (Francis, 1981). The second is that the method that is used to determine the position of the regional boundaries excludes a number of factors that influence spatial weather patterns. Rather, multivariate techniques that allow a range of factors, such as distance from sea, altitude, aspect, and topography, to be considered are likely to provide better defined weather zones than the current methodology (Aspinall *pers. comm.*, 1995). It should be noted, however, that various procedural and data related issues would need to be addressed if improved methods of defining the weather zones are adopted. Although, it is likely that the methodological issues involved with establishing the weather zones could be overcome (Aspinall *pers. comm.*, 1995), difficulties associated with obtaining potentially greater amounts of weather data would not be easily resolved (Peiris *pers. comm.*, 1995).

As mentioned above, three possible climates, four regions, and ten years of weather scenarios are considered in this study. Compared with various other studies (see for example Topp and Doyle, 1996b; Yiqun *et al.*, 1994), this represents a relatively small number of weather series. If a greater number of climatic scenarios are included in this study it would be possible to evaluate the sensitivity of farming systems against a wider range of weather conditions. For example, changes in

Figure 2-1. Weather Zones in Scotland.



farming systems that are the result of variations in the incidence of extreme weather events might be considered. Also, if parameters in the LP models are estimated using weather series of longer duration, for example 30 year scenarios are commonly used in climatic studies (MacKerron *pers. comm.*, 1995), this might increase the statistical confidence that can be placed in the model. However, the large amount of information relating to non-weather factors that are present in the model, such as soils, crops, planting dates, nitrogen application rates, animal types and stocking rates, has meant that computing considerations have restricted the range of weather data that could be included.

2.2 Results.

The results of the weather simulations that were performed using Peiris and McNicol's model can be found in Table 2-1 to Table 2-5. Mean daily temperatures are presented in Table 2-1. The results suggest that Wick is the coldest region and in increasing order of temperature it is followed by Mylnefield, Kinloss and Paisley. The mean annual temperatures of these regions are respectively 7.5, 8.3, 8.4 and 9.0°C. The differences in regional temperatures appear to be principally due to differences in summer temperatures and to a lesser extent to differences in spring and autumn temperatures. In winter only small differences in temperature are evident.

As the influence of a change in climate is to add approximately 3°C throughout the year, the ranking of the regions in terms of temperature is the same for all of the climatic scenarios. The inter-regional differences in temperatures of approximately 1.5°C between the coldest and warmest regions is considerably less than the difference of 3°C that is postulated for the climate change scenarios. Although temperature is only one of several weather variables that affect crop growth, the between climate differences in temperature suggest that the impact of climatic change on crop production may be greater than the current influence of regional differences in temperature. For further discussion of the influence of temperature on crop productivity see Section 5.3.

With respect to rainfall (see Table 2-2), Paisley is the wettest region and is followed by Wick, Mylnefield and Kinloss. For the current climate the mean annual rainfall of these regions is 1080, 750, 640 and 560 mm, respectively. The annual

Table 2-1. Mean Daily Temperature. (° Celsius)

Region	Kinloss			Mylnefield			Paisley			Wick		
Climate	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’
January	2.5	6.0	5.9	2.0	5.4	6.6	2.5	6.0	5.9	2.6	5.9	6.1
February	2.8	6.0	6.7	2.8	5.8	6.5	3.7	6.7	6.5	3.3	6.3	6.2
March	4.9	7.3	8.0	5.0	7.4	8.4	5.3	8.6	8.7	4.4	6.8	6.9
April	7.8	10.3	10.4	7.8	10.0	10.1	8.3	10.9	11.4	6.4	9.6	9.5
May	10.3	13.3	13.5	9.7	13.1	13.3	11.4	14.6	14.6	8.6	12.3	11.2
June	12.6	16.1	15.9	13.0	16.5	16.6	14.2	17.0	17.1	11.0	14.5	14.0
July	13.5	17.0	17.5	14.2	16.9	17.1	15.2	17.9	18.0	12.3	15.4	15.5
August	14.0	17.3	16.1	14.3	17.4	17.1	15.0	17.5	17.5	11.9	15.3	15.5
September	12.2	14.8	15.6	11.8	15.3	15.0	12.7	15.9	16.2	11.2	14.2	14.2
October	9.3	12.8	12.5	9.1	12.0	11.9	9.7	13.1	12.8	8.8	11.9	11.5
November	6.6	9.3	9.4	6.0	9.9	8.6	6.5	9.4	9.4	6.4	9.5	9.7
December	4.2	6.7	7.0	3.5	6.3	7.0	3.8	7.1	8.1	3.6	7.1	7.4

Table 2-2. Mean Daily Rainfall (mm / day)

Region	Kinloss			Mylnefield			Paisley			Wick		
Climate	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’
January	1.2	2.1	1.3	2.0	2.5	1.5	3.4	3.8	3.0	2.2	3.6	2.2
February	1.8	2.1	1.2	2.3	3.0	2.2	3.2	4.3	3.1	2.2	3.4	2.5
March	1.9	2.1	1.2	2.0	2.8	2.3	3.2	3.6	2.7	2.2	3.0	2.2
April	1.4	1.7	1.1	1.6	2.4	1.7	2.5	2.2	2.1	2.1	2.5	2.0
May	1.3	1.5	1.2	1.4	2.0	1.7	2.8	2.3	1.8	1.8	1.9	1.5
June	1.6	1.6	1.6	1.5	1.6	1.3	1.9	2.3	2.5	1.4	1.5	1.4
July	1.4	1.4	1.4	1.6	1.6	1.2	2.2	2.5	2.4	1.2	1.5	1.4
August	1.4	1.4	1.5	1.4	1.6	1.6	2.5	2.6	2.2	2.1	1.7	1.7
September	1.6	1.6	1.3	1.9	1.7	1.9	3.4	3.1	3.2	2.3	2.1	2.7
October	1.8	2.2	1.7	1.9	2.5	2.1	3.7	5.1	3.7	2.6	3.5	2.7
November	1.2	2.2	1.6	1.7	2.4	2.0	3.9	4.0	3.8	2.3	3.4	2.1
December	1.7	2.1	1.4	1.7	2.6	1.6	2.9	4.1	2.4	2.3	2.8	2.3

rainfall at Kinloss, therefore, is approximately half the value at Paisley. Also, seasonal variations in rainfall are most marked at Paisley which in relative terms has wet winters and dry summers. By comparison seasonal differences in precipitation are proportionally smaller at Wick and Mylnefield and at Kinloss rainfall tended to occur at a relatively constant rate throughout the year. A comparison of annual rainfall totals showed approximately a 20 percent increase between the current climate and climate '1' and that this varied between a 12 percent increase at Paisley and a 27 percent increase at Mylnefield. However, the ranking of the regions in terms of rainfall did not change from the current climate. Also, there appears to be a small increase in the seasonality of rainfall when comparing climate '1' with the current climate. As a final point there are some minor differences in rainfall between the current climate and climate '2' but these are likely to be due to random variation (Peiris *pers. comm.*, 1995).

The estimates of differences in photosynthetically active radiation (see Table 2-3) appeared to be relatively insensitive to changes in climate. The estimates derived from Peiris and McNicols model suggest that for the current climate that Mylnefield receives the most radiation and that Paisley, Wick and Kinloss are exposed to lesser amounts of radiation. For the current climate the average daily incidence of radiation at these sites is 8500, 7940, 7580 and 7350 kJ per m^2 per day which represents a difference of approximately 14 percent between the most and least sunny regions. For climate '1' the ranking of the regions in descending order of annual radiation is Mylnefield, Wick, Paisley and Kinloss. Although the ranking of the regions differs slightly from that achieved for climate '0' the difference in radiation between these climates is in all cases less than 4 percent. The ranking of the regional radiation totals is the same for the current climate as for climate '2'. Also, the magnitude of differences between climates '0' and '2' is similar to the differences between climates '0' and '1'.

The estimates of wind speed (see Table 2-4) suggest that for the current climate that Wick is the windiest region with a mean annual wind speed of 5.7 metres per second. Kinloss is next windiest with a mean wind speed of 5.1 metres per second. At Paisley and Mylnefield the estimates of wind speed are, respectively, 3.4 and 3.3 metres per second. As in the case of rainfall, the seasonality of wind speed is greatest for the windier regions, with windy winters and relatively calmer summers, and least for the regions that had less wind. The estimates of wind speed appeared to be relatively insensitive to changes in climate with variations between climate '0'

Table 2-3. Mean Daily Photosynthetically Active Radiation (kJ / m^2 / day)

Region	Kinloss			Mylnefield			Paisley			Wick		
Climate	'0'	'1'	'2'	'0'	'1'	'2'	'0'	'1'	'2'	'0'	'1'	'2'
January	1748	1879	1778	2091	2477	2079	2155	2041	2265	1878	2006	2085
February	2764	2972	3176	3569	3492	2976	3274	3172	3248	3273	3122	3381
March	4797	5251	5668	6139	6093	5670	5345	5029	5571	5715	5764	6451
April	8994	8924	9276	10554	9685	9969	9721	8738	9518	9366	9307	10320
May	14080	12967	12732	15244	14041	14815	15205	14602	15416	13359	13601	14526
June	17591	17091	14805	18201	20018	19631	18827	16727	16584	15116	16186	15531
July	14393	17497	14512	18127	16853	18089	16573	16125	16270	15543	16131	14785
August	10469	11985	10019	12562	11242	12190	10372	11120	10804	11178	11272	10531
September	6500	6376	6460	7116	7160	7470	6501	6458	6208	7229	7045	6759
October	3413	3218	3344	4192	4098	3886	3523	3563	3551	4111	3659	3926
November	2121	1763	1778	2433	2353	2148	2112	2324	2191	2475	2102	2295
December	1342	1289	1527	1842	1840	1894	1642	1607	1757	1710	1674	1694

Table 2-4. Mean Wind Speed (m / second)

Region	Kinloss			Mylnefield			Paisley			Wick		
Climate	'0'	'1'	'2'	'0'	'1'	'2'	'0'	'1'	'2'	'0'	'1'	'2'
January	5.7	5.9	5.3	3.4	3.6	4.5	3.3	3.9	4.0	7.0	6.6	6.7
February	5.5	5.5	5.9	3.8	3.7	4.2	3.8	3.6	3.7	6.6	7.0	6.6
March	5.3	4.8	5.5	3.7	4.1	3.8	3.4	3.7	3.7	6.1	6.0	6.1
April	4.4	5.2	5.0	3.7	3.6	3.8	3.1	3.6	3.5	5.3	5.7	5.7
May	4.8	4.2	4.9	3.2	3.2	3.5	3.2	3.4	3.3	5.3	5.6	5.0
June	4.4	4.0	4.4	3.0	3.4	3.6	3.2	3.0	2.8	4.7	4.8	4.8
July	4.4	4.8	4.1	2.9	2.9	3.0	3.3	2.9	3.3	4.7	5.1	4.5
August	4.7	4.5	4.5	3.3	3.2	3.2	3.0	2.8	3.1	4.6	4.8	5.1
September	4.3	5.1	4.4	2.9	3.3	3.2	3.4	3.3	3.2	5.1	5.2	5.2
October	5.7	5.5	5.0	3.1	3.4	3.2	3.6	3.5	3.0	6.1	5.9	5.9
November	6.5	5.8	5.6	3.4	3.7	3.7	3.7	3.6	3.4	6.3	6.4	6.3
December	5.5	5.8	5.1	3.6	3.3	3.7	4.3	3.9	4.1	6.8	6.8	6.5

and climate '1' ranging between -0.2 percent and 3.5 percent. Between climates '0' and '1' variations in wind speed ranged from a reduction of 2.5 percent and an increase of 8.5 percent. The difference in the windiness of the regions tended to be greater, therefore, than differences that arise with a change in climate.

The last of the weather variables that are considered by Peiris and McNicol is vapour pressure (see Table 2-5). For all of the regions and climates a strong seasonal pattern in vapour pressure is evident with higher pressures occurring in summer. For the current climate the highest mean annual vapour pressure is recorded for Paisley at 1.02 kPa. There is little difference between the other regions with respect to this measure as the mean vapour pressure of these regions are all approximately 0.89 kPa. The mean vapour pressure for climates '1' and '2' are approximately 20-25 percent greater than for climate '0'. The magnitude of these differences suggests that a relatively strong relationship exists between vapour pressure and temperature.

2.3 Conclusions.

In conclusion rainfall, temperature, and vapour pressure are relatively sensitive to changes in climate in comparison to radiation and windiness which are less sensitive. In particular the magnitude of temperature and vapour pressure changes with changes in climate are greater than existing inter-regional differences. For the other weather variables inter-climate differences are smaller than inter-regional differences. It should be noted, however, that climatic change of the scale estimated by Peiris and McNicol is still likely to cause significant changes in farming systems, particularly when existing inter-regional differences in agriculture are considered. For the current climate Paisley is the warmest and wettest region and has the highest mean vapour pressure; Wick is the coldest and windiest region; Kinloss is the driest region and receives the least radiation; and Mylnefield receives the most radiation but is the least windy region. A further point is that although there are some changes in the ranking of the regions the relative differences between regions tended to be preserved for the different climates.

Table 2-5. Mean Vapour Pressure (kPa)

Region	Kinloss			Mylnefield			Paisley			Wick		
Climate	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’
January	0.6	0.8	0.8	0.6	0.8	0.8	0.7	0.8	0.8	0.6	0.8	0.8
February	0.6	0.7	0.8	0.6	0.8	0.8	0.7	0.8	0.9	0.6	0.8	0.8
March	0.7	0.8	0.8	0.7	0.8	0.9	0.8	0.9	1.0	0.7	0.8	0.8
April	0.8	0.9	1.0	0.8	0.9	0.9	0.9	1.1	1.1	0.8	1.0	1.0
May	1.0	1.2	1.2	0.9	1.1	1.1	1.1	1.3	1.3	0.9	1.1	1.1
June	1.1	1.3	1.3	1.1	1.4	1.4	1.3	1.5	1.5	1.1	1.4	1.3
July	1.2	1.4	1.5	1.2	1.4	1.4	1.4	1.7	1.7	1.2	1.5	1.5
August	1.2	1.5	1.4	1.2	1.5	1.5	1.4	1.7	1.7	1.2	1.5	1.5
September	1.1	1.4	1.4	1.1	1.4	1.3	1.3	1.6	1.6	1.1	1.4	1.4
October	0.9	1.2	1.2	1.0	1.2	1.2	1.1	1.4	1.3	1.0	1.2	1.2
November	0.8	1.0	1.0	0.8	1.0	0.9	0.9	1.1	1.1	0.8	1.0	1.1
December	0.7	0.8	0.8	0.7	0.8	0.9	0.7	0.9	1.0	0.7	0.9	0.9

3. FARM TYPOLOGY.

3.1 Introduction.

In this study a farm typology is established using multivariate cluster analysis techniques. The purpose of this typology is to determine an appropriate structure for the farm type sub-models. As mentioned in Section 1.1, the national level model consists of a series of regional sub-models which are themselves comprised of farm sub-models. It is essential therefore to establish an accurate description of the asset structure and the production possibilities that are available to different farm types if the national model is to provide a realistic portrayal of Scottish agriculture. The chapter is in three sections. The rationale for establishing the typology and the principle sources of data are considered in the first section. In the second section the methodology that is used to create the farm typology is presented and the variables that are included in the typology are discussed. Some of the issues associated with aggregation bias are also presented. The results of the farm typology can be found in the final section.

To the extent that the resulting typology reflects the production opportunities that are available to farms, the approach that is adopted here, differs from the farm types that are used by SOAEFD. The SOAEFD farm typology is often used for national economic reporting and classifies farms according to the enterprises that occur on farms. The relative balance of sheep, cattle, and cropping activities, and also whether a farm is located in a Least Favoured Area (LFA) are the major determinants of the SOAEFD farm types. For a formal definition of the SOAEFD farm types see Table 3-1.

The data that is used to establish the farm typology is principally derived from the Farm Accounts Scheme FAS). The FAS, which is commissioned by SOAEFD and is updated on an annual basis, is a database of the technical and financial performance of a sample of approximately 600 farms or 2 percent of the farms in Scotland. The FAS provides a highly detailed source of technical and financial data and is used by both SOAEFD and the European Commission to monitor the economic performance of Scottish farms and also to evaluate the response of farms to policy initiatives (Anderson *pers. comm.*, 1996). A possible criticism of the FAS, however, is that the scheme may not provide a normal representation of Scottish farms due to the voluntary membership of contributing farmers. However, any bias arising from this source is unlikely to be significant with respect to this study (Mainland *pers. comm.*, 1996).

Table 3-1. SOAEFD Farm Types[4].

Type of Farm.	Definition
1: Specialist Sheep (LFA)	Farms in the less favoured areas with more than two-thirds of the total standard gross margin coming from sheep.
2: Specialist Beef (LFA)	Farms in the less favoured areas with more than two-thirds of the total standard gross margin coming from cattle.
3: Cattle and Sheep (LFA)	Farms in the less-favoured areas with more than two-thirds of the total standard gross margin coming from sheep and beef cattle together.
4: Lowground Cattle and Sheep.	Farms not in the less-favoured areas with more than two-thirds of the standard gross margin coming from sheep and beef cattle together.
5: Cereals.	Farms where more than two thirds of the total standard gross margin comes from cereals and oilseeds.
6: General Cropping.	Other farms where more than two-thirds of the total standard gross margin comes from all crops.
7: Dairy.	Farms where more than two-thirds of the total standard gross margin comes from dairy cows.
8: Mixed.	Farms where no enterprise contributes more than two thirds of the total standard gross margin.

3.2 Methodology.

3.2.1 Variables Included in Typology.

The outputs that are used to classify farms in terms of the SOAEFD farm typology are influenced by the presence of inputs or resources, such as land quality, livestock, capital, machinery and building complements. However, the value of the SOAEFD farm types is limited with respect to this study, as the SOAEFD typology only

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[4] Source: SOAEFD (1997).

provides an indirect indication of the resources that are available to farms. In this study, an effort was made to explicitly incorporate variables that relate to resource availability, as it was thought that the inclusion of such variables would yield a typology that was better suited to evaluating potential changes to farming operations. The reason for this is that farm assets influence not just the activities that occur on a farm, but also the ability of the farm to alter its operations in response to a change in conditions. The factors that are considered in the typology, therefore, include not just variables that relate to the proportion of farm income that is derived from various sources (milk, cattle, sheep, and crops), but also variables that relate to: the quality of the land on the respective farms; the farm business size[5], and whether or not the farm is sited in a LFA[6].

The variables that are included in the farm typology, therefore, represent a mix of input and output variables. The variables that relate to the proportion of income that is derived from different animal types and from cropping, are similar to the variables included in the SOAEFD farm typology, and reflect to some extent, the capital structure of the farms. This is because the animals, buildings and machinery that are necessary to generate income on a farm involve capital investments. The fixity of these investments means, at least in the short term, that it is difficult for farmers to alter the composition of farm output. Over an intermediate or longer term, however, the mix of such capital items and hence the output that is produced can be varied by farmers.

As mentioned above, variables that reflect land quality are included in the typology. Land is usually the single largest item of capital expenditure on a farm (Anderson *pers. comm.*, 1996). Further, land quality places a significant limit on the range of activities that can be performed, and also on the productivity of crops and forages that can be achieved on a farm. In the current study the available water holding capacity (AWC) of soils is used as a predictor of the potential productivity of a soil. The processes that govern relationships between AWC and subsequent transpiration and growth of crops are relatively well understood and are often used in modelling studies of crop growth (see for example Aslyng and Hansen, 1982; Jefferies and Heilbronn, 1991; Porter, 1993; Rimmington and Charles-Edwards, 1987a and 1987b; Whisler *et al*, 1986). Although a number of other physical and chemical factors also influence

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[5] In the current context farm business size was measured in terms of European Size Units. See SOAEFD (1995) Economic Report on Scottish Agriculture.

[6] It should be noted that the SOAEFD farm types also include LFA status as a variable.

soil quality, for example soil texture, drainage, acidity and organic matter content, there are positive correlations between the productivity of a soil and AWC (Vinten *pers. comm.,* 1996).

To estimate the AWC variables that are included in this study it was first necessary to determine the area of the soil associations that are present on the member farms of the FAS. This was achieved by asking co-operating farmers to outline their farm boundaries on an ordinance survey map (see Appendix 1). The information from these maps was then digitised and used within a GIS. This procedure allowed the digitised boundary information to be interfaced with the regions defined in this study, and also with digital maps of Scottish soil associations (Aspinall *pers. comm.,* 1995). The outputs of the procedure includes the area of each farm that corresponds to each weather zone and each soil association. The AWC's of the soil associations were then estimated from a database of Scottish soils (Bouma *et al,* 1981; MacDonald *pers. comm.,* 1995; see Appendix 2). A description of this database can be found in Brown *et al* (1987) and MacDonald *et al* (1994)[7].

Farm business size is included in the farm typology as the capital structure of farms and requirements for labour tend to vary as a function of farm size (Buckwell and Hazell, 1972) (see Table 3-2). The final variable included in the farm typology relates to whether a farm is in a LFA. LFA farms are designated as being present in economically disadvantaged areas that tend to be distant from major markets and because of their agro-climatic characteristics, the farms are likely to be restricted in their production possibilities (Anderson *pers. comm.,* 1996). In an effort to improve the economic position of LFA's, preferential treatment is given in the form of grant aid from national and European funding bodies. As these payments can affect the intensity and types of production activities that occur it was desirable to include the LFA status of farms in the typology.

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[7] To simplify the manipulation of data the soil associations were classified into four categories where each class had a similar number of entries. The range of AWC's in these categories is 0-65, 65-80, 80-95, 95-∞ mm. Each category was then assigned an AWC that approximates the median value of the respective classes: that is 50, 72.5, 87.5 and 110 mm.

Table 3-2. Definition of SOAEFD Farm Business Size Units[8].

Small:	8-39.9 ESU	- this approximately represents farm with a single labour unit.
Medium:	40-99.9 ESU	- this approximately represents a farm with two to three labour units.
Large:	100-199.9 ESU	- this approximately represents farms with more than three labour units.

Although the list of variables that are present in the farm typology is not exhaustive, the variables that reflect the principle assets and constraints of farms are represented. Other variables that could have been incorporated in the farm typology, include factors such as technology availability, managerial ability, and expectations about unit returns by farmers (Day, 1963a). However, there are difficulties with collecting data to represent these variables. Also, it is likely that the inclusion of additional variables would reduce the transparency of the resulting typology. The variables that are selected reflect a compromise in terms of simplicity, and the ability of the typology to achieve its intended purpose; that is to establish farm groups that possess homogenous production possibilities.

3.2.2 Cluster Analysis Methods.

Cluster analysis is a generic term that refers to techniques that differentiate between objects on the basis of descriptive variables that are associated with the objects (Gordon, 1981; Plackett, 1981). The purpose of a cluster analysis, therefore, is to form groups of objects, in this case of farms, that are distinct from one another, but which are internally cohesive (Everitt, 1993). In recent years a high level of scientific interest has focused on cluster analysis and because of this a wide range of algorithms and statistical theory is available in the literature. A comprehensive review of the subject is given by McCormack (1971). Other reviews can be found in Hand (1981) and Karson (1982).

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[8] This is defined in terms of total standard gross margin (average value 1987 to 1989), with 1200 ECU (European currency units) of standard gross margin corresponding to one ESU (European Size Unit). Source: SOAEFD (1997).

In this study, the farm typology is established using a hierarchical clustering technique called complete link or furthest neighbour. This technique is an agglomerative method whereby farms are initially represented as n separate clusters that each contain a single farm. The clusters are then successively joined to the closest neighbouring cluster, so that after n-1 stages, a single cluster contains all of the farms. The outcome of this process is often represented as a hierarchical tree or dendogram whose nodes indicate the points at which groups are fused. The farm typology is created by cutting the dendogram at a level that ideally corresponds to a point where there is a sharp reduction in the number of groups but only a small reduction in the homogeneity of the groups. The clusters that result from this procedure are sometimes represented as the point at which the branches of the dendogram are cut.

The statistical package used to perform the cluster analysis is Genstat (1994). The first step of the procedure involves estimating the similarity of farms to one another by establishing a univariate measure of association from the variables that differentiate the farms. The measure of association that is selected conforms to the method of Gower (1971) and is the default method used in Genstat. Gower's measure of association is well suited to this study as variables can be quantitative, qualitative, dichotomous, or a mixture of these types. The technique is also robust with respect to missing values (Genstat, 1994). In the current study, there are two qualitative variables (LFA status, and SOAEFD farm business size code), and eight quantitative variables (four relating to the proportion of farm income derived from alternate sources, and four relating to the proportion of farm land in the AWC categories 0-65, 65-80, 80-95, and 95-∞ mm). The calculated measures of association form a symmetric matrix that estimates the degree of similarity between all pairs of included farms.

As mentioned above, the cluster analysis involved gathering farms into groups using a technique called complete link or furthest neighbour. Complete linking involves successively joining groups that are closest to one another, where the proximity of groups is defined in terms of the measure of similarity of the most distant farms in the respective groups. For other methods, such as single link or centroid clustering the method of defining the closest neighbour differs from complete linking (Everitt, 1993). For example the distance between groups in single linkage clustering is defined in terms of the closest farms in the respective groups, whereas centroid linking involves calculating an average measure of association between farms that comprise a group, and comparing this with similarly obtained averages from other groups.

Complete linkage is used to perform this cluster analysis because of the characteristics of the resulting typology. A difficulty with single linkage clustering is that the method can produce disparate groups where members have little in common except that they are connected by a series of intermediate points. In contrast, complete linkage tends to produce relatively compact clusters. Intermediate between these methods is centroid linking, which in general produces groups that have lower homogeneity but higher seperability than complete linkage clustering (Hunter *pers. comm.*, 1996). In this study, it is considered desirable to form farm groups that have a high degree of cohesiveness; single linkage and centroid clustering are therefore excluded from the analysis.

A difficulty with hierarchical methods, however, is that the groups are irrevocably fused so that objects that are poorly classified in the initial stages of an analysis can not be reallocated. A related point is that major groups can be spuriously influenced by the chance joining of small units early in an analysis. Other objections to hierarchical techniques have also been raised in terms of the mathematical properties of the resulting groups (see for example Jardine and Sibson, 1968). In response, a number of researchers have suggested that more acceptable classifications can be achieved using non-hierarchical methods (Hand, 1981). In general, non-hierarchical methods work by partitioning objects between a specified number of groups so that some criterion (such as the within group sum of squares) is optimised.

However, with non-hierarchical clustering methods, it can be difficult to locate a grouping that optimises the selected criterion. Even small numbers of objects and groups can give rise to a very large number of feasible partitions. For this reason search procedures that only evaluate a sub-set of possible groupings tend to be used to find the optimum. Although search procedures are more efficient than exhaustively evaluating all possible partitions they do not guarantee that a global solution will be identified. It is usually necessary therefore to commence a search from a number of different starting positions so that confidence in a typology can be achieved. In contrast, hierarchical methods give a single solution, and in the current situation produced acceptable results. In this study it is considered that little benefit would be gained by performing a non-hierarchical cluster analysis (Hunter *pers. comm.*, 1995).

The resulting farm typology involved a compromise between classifying farms into groups that are sufficiently small in number to be represented in the model and avoiding aggregation bias in the analysis. In any hierarchical cluster analysis the initial fusions of groups correspond to a relatively small fall in the measure of within group similarities. However, as the number of groups becomes smaller the drop in within group similarity becomes greater. As the measure of similarity indicates variations between farms that are contained in the same group, the lower the measure of similarity, the more likely that aggregation bias may be present in the typology. In the current study aggregation bias presented a potentially significant source of error and is discussed in the following section.

3.2.3 Aggregation Bias.

Aggregation bias exists when the solution vector for the representative farm model is different to that produced by programming the farms individually (Spreen and Takayama, 1980). Day (1963a) defined a comprehensive set of conditions for linear static models, that are sufficient to exclude aggregation bias, these are (1) technological homogeneity, where each farm has the same production possibilities, and the same levels of technology, and managerial ability; (2) pecuniary proportionality, where the expectations of individual farmers about farm returns are proportional to the average expectations of the group; and (3) institutional proportionality, where the constraint vector of an individual farm model is proportional to the constraint vectors of other farms in the same group. These conditions were subsequently extended to account for dynamic models (Day, 1963b and 1964), but the additional requirements are strict and have implications for the constraint vector that may limit a model's ability to fulfil its objectives. Buckwell and Hazell (1972) suggest that the modeller may have to accept some small level of bias, if the structure of a representative farm model is to be adequate for its intended purpose.

With regard to Day's (1963a) requirement for technological homogeneity, the proportion of land quality classes that comprise a farm, is considered to be the most important determinant of the production possibilities of a farm. Technologies are often specific to a particular soil and climate; so that along with productivity levels, technologies tend to be related to land quality; it is assumed that disaggregation of the farm typology by weather zone (or region), would further increase technological and productive uniformity in the resulting farm groups. Managerial ability is also mentioned by Day as a criteria for discriminating between farm types, however, the difficulty of obtaining appropriate data precluded the use of this variable in the model.

Turning to pecuniary proportionality, Buckwell and Hazell (1972) suggest that both enterprise productivity's, and the prices received for outputs, should be the same for farms belonging to the same group. In the current model, crop and animal yields are endogenously modelled variables, so that productivity levels are relevant to the requirement for technological homogeneity, rather than pecuniary proportionality, a requirement that, as discussed above, the model should fulfil. This leaves input and output prices. Buckwell and Hazell argue that agricultural prices are significantly affected by government intervention, so that farmers tend to hold uniform expectations across quite large areas. As Scotland is a relatively small country and because the farm typology is stratified into four regions, it is considered unlikely that significant errors would arise from this source. The last of Day's requirements, institutional proportionality, relates to the resource structure or the constraint vector of the farm model. When the variables in the cluster analysis were selected an effort was made to incorporate the principle assets of a farms structure. Although some aggregation bias is likely to be present in the model it is argued that the clustering procedure that has been implemented means that these errors should be relatively small.

3.3 Results.

The sample of farms that is used in the typology contained 586 farms. Data relating to the quality of land (see discussion above) was collected for 368 or 63 percent of the farm sample. Other data that is used in the typology was collected from the 1995 FAS database and is available for all farms in the sample. This data included the LFA status of the farms (wholly outside, less than 50 percent inside, more than 50 percent inside and wholly inside), the farm business size (small, medium or large), and the proportion of the farms income that is derived from different sources (sales of milk, cattle, sheep, and crops).

The results of the analysis show a large fall in the measure of within group similarities after five farm groups are formed. A subjective examination of the five farm groups suggests that the groups are relatively cohesive and also that the groups are distinct from one another. The typology involving five farm groups is accepted as five farm groups are considered sufficient to represent Scottish agriculture and also because the number of farm groups is small enough to be reasonably represented in the model. The selected farm types are identified with respect to the major sources of income. These are (1) 'cattle and sheep', (2) 'dairy', (3) 'sheep', (4) 'cropping' and (5) 'cropping and cattle'. The principle features of the typology are presented in Table 3-4 to Table 3-7.

From Table 3-4, it can be seen that there are relatively large differences between the selected farm types. The results of the typology indicate that for 'cattle and sheep' farms approximately 60 percent of farm income is derived from cattle sales, 28 percent from sheep sales and 12 percent from the sale of crops. 'Cattle and sheep' farms are the largest of the identified groups and contained 324 farms or 55 percent of the total sample. 'Dairy' farms are the next largest group with 104 farms or 18 percent of the sample. On 'dairy' farms approximately 63 percent of farm income is derived from milk sales and 26 percent from the sale of cattle. An examination of individual farm records indicated that the majority of cattle sales on 'dairy' farms are derived from bobby calves and cull cows. In contrast the proportion of 'dairy' farm income that is derived from sheep and crops is much less at 4 and 7 percent.

'Cropping' farms comprised the third largest group and included 76 farms or 13 percent of the FAS sample. On 'cropping' farms the sale of crops accounts for 79 percent of income and 'cattle and sheep' account for 13 and 8 percent of income, respectively. The fourth largest group with 63 farms or 11 percent of the FAS sample are 'sheep' farms. On 'sheep' farms, 88 percent of the income is derived from the sale of sheep and wool; while cattle and crops account for 7 and 5 percent of income. Of the farm types considered in this study, 'sheep' farms are the most specialised in terms of the proportion of farm income derived from a single enterprise. The farm group with the smallest number of farms is 'cropping and cattle' which included 19 farms or 3 percent of the FAS sample. 'Cropping and cattle' farms are the least specialised of the farm types and achieved a moderate level of income from all of the sources considered in the typology. On the 'cropping and cattle' farm type, the proportion of farm income that is derived from milk, cattle, sheep and crops is 10, 38, 15 and 37 percent, respectively.

Table 3-3. Number of Farms in Farm Accounts Scheme.

Farm Type	Region				
	Kinloss	Mylnefield	Paisley	Wick	Total
'Cattle and sheep'	86	65	123	50	324
'Dairy'	14	8	77	5	104
'Sheep'	6	11	35	11	63
'Cropping'	16	56	4	0	76
'Cropping and cattle'	6	11	2	0	19
Total	128	151	241	66	586

Table 3-4. Source of Income by Farm Type (percent).

Farm Type	Income			
	Milk	Cattle	Sheep	Crops
'Cattle and sheep'	0	60.2	28.1	11.7
'Dairy'	63.3	26.0	4.0	6.6
'Sheep'	0	6.7	88.4	4.9
'Cropping'	0.4	13.1	7.6	78.8
'Cropping and cattle'	10.0	37.6	15.3	36.9

Table 3-5. Less Favoured Area Status by Farm Type (percent).

Farm Type	Less Favoured Area Status			
	Wholly Outside	Mainly Outside (< 50 % LFA)	Mainly Inside (> 50 % LFA)	Wholly Inside
'Cattle and sheep'	21.6	2.7	6.7	68.8
'Dairy'	38.5	2.8	4.8	53.8
'Sheep'	1.6	3.2	4.7	90.4
'Cropping'	96.1	0	0	3.9
'Cropping and cattle'	21.1	31.6	42.1	5.2

With regard to the LFA status of the farm groups, the majority of farms are either wholly outside or wholly inside the LFA and relatively few farms are partly inside the LFA. The 'cropping and cattle' farm type is unusual in this respect as the majority of these farms are partially inside the LFA. With respect to 'cattle and sheep', 79 percent of farms are either wholly or partly inside the LFA schemes. This compares with 62 percent of 'dairy' farms that are at least partially inside the LFA schemes. 'Dairy' farms with 38 percent are second only to 'cropping' farms in terms of the percentage of farms that are wholly outside the LFA's. 'Sheep' farms are heavily concentrated in the LFA's with 98 percent of farms wholly or partly present in the

LFA schemes. In contrast 96 percent of 'cropping' farms are wholly outside the LFA scheme.

Many of the 'cropping and cattle' farms appear to be situated on the periphery of LFA schemes with 21 percent wholly outside, 32 percent mainly outside and 42 percent mainly inside the less favoured areas. Only 5 percent of 'cropping and cattle' farms are wholly inside the LFA's. This suggests that 'cropping and cattle' farms occupy land that is transitional between LFA and non-LFA land. The results of the typology suggest that the farm systems can be ranked in terms of LFA status as follows: 'cropping', 'dairying', 'cropping and cattle', 'cattle and sheep', and 'sheep'. 'Cropping' farms appear to be the most intensive farm type and have the least LFA land, while 'sheep' farms appear to be the least intensive and have the most LFA land.

In terms of farm size approximately 70 percent of the 'cattle and sheep' and 'sheep' farms are classed as medium sized farm businesses. On 'cattle and sheep' farms approximately 19 percent are classified as large and 7 percent as small. On the 'sheep' farms, the proportion of large and small businesses is 5 and 24 percent, respectively. For the other farm types ('dairy', 'cropping', and 'cropping and cattle'), approximately 53 - 63 percent of farms are classed as large and fewer than 2 percent are classed as small. The ranking of the average AWC of the farms from highest to lowest is 'cropping', 'cropping and cattle', 'dairying', 'cattle and sheep', and 'sheep'. The ranking of farm types by differences in average AWC gives a similar result to the ordering of farm types by LFA status and approximates the order of farms between highest and lowest potential land use.

The results of the typology are used to establish the structure of the farm type sub-matrices and also to specify the right hand side (RHS) coefficients that define the availability of resources on the various farm types and for each of the regions. The activities and constraints that are included in the model are selected on the basis that they are relevant to the principle sources of income, that is greater than 20 percent of total farm income, of the farm types. A summary of the variables included in each of the farm type matrices is presented in Table 3-8. The RHS values that are included in the model are calculated as a mean of the resources associated with the various farm types. The RHS coefficients that are varied between farms and regions include: land of differing qualities; working capital position at the start of the year; capital and interest repayments; and numbers of capital livestock (beef, dairy and sheep).

Table 3-6. SOAEFD Farm Business Size by Farm Type (percent).

Farm Type	Farm Business Size		
	Small	Medium	Large
'Cattle and sheep'	7.4	73.7	18.8
'Dairy'	0.9	46.1	52.8
'Sheep'	23.8	71.4	4.7
'Cropping'	2.6	38.1	59.2
'Cropping and cattle'	0	36.8	63.1

Table 3-7. Average Area of Farm Types and Composition of Farm Types: AWC of Soils (percent).

Farm Type	Average area (hectare)	Soil AWC (mm)			
		0 - 65	65 - 80	80 - 95	95 - ∞
'Cattle and sheep'	352	17.3	37.5	37.0	8.1
'Dairy'	126	12.1	29.0	32.6	26.2
'Sheep'	552	23.4	48.7	22.2	5.6
'Cropping'	152	6.1	22.0	40.1	31.7
'Cropping and cattle'	299	6.1	25.4	39.7	28.6

Table 3-8. Variables Included in the Farm Type Sub-Matrices.

Activities	Farm Types				
	'Cattle and sheep'	'Dairy'	'Sheep'	'Cropping'	'Cropping and cattle'
Animals: Cattle	•				•
: Sheep	•		•		
: Dairy		•			
Crops : Forage	•	•	•		•
: Arable				•	•
Fertiliser	•	•	•	•	•
Finance	•	•	•	•	•
Labour	•	•	•	•	•
Machinery and buildings	•	•	•	•	•

Table 3-9. Average Financial Status of Farms (£ / farm).

Farm Type	Cash at Start of Year	Debt repayments
'Cattle and sheep'	4928	5161
'Dairy'	5837	7969
'Sheep'	10274	2281
'Cropping'	4910	9630
'Cropping and cattle'	2146	15310

Table 3-10. Average Number of Mature Breeding Livestock per Farm (animals / farm).

Farm Type	Animal Type		
	Cattle	Dairy	Sheep
'Cattle and sheep'	24	0	180
'Dairy'	0	42	0
'Sheep'	0	0	404
'Cropping'	0	0	0
'Cropping and cattle'	39	0	0

4. DANTZIG-WOLFE DECOMPOSITION.

4.1 Introduction.

Many linear programming models of complex systems are comprised of independent sub-systems that are coupled by global constraints. LPs that consist of coupled sub-systems can sometimes be described as having block-angular structures. A feature of block angular models is that the linkages in a particular sub-system are relatively dense compared with the linkages between the sub-systems. An example of such a problem is a series of national economies that are linked to other economies by international trade or finance (Ho and Loute, 1981). Another example might be where the sub-systems are comprised of regional production systems that are coupled by inter-regional trade or by requirements for common resources. In 1960, Dantzig and Wolfe (1960) introduced a method to solve block-angular problems that involves decomposing the initial problem into a master problem and a series of sub-problems. A solution to the global problem is then obtained by alternating between solving the master problem and the set of sub-problems.

Essentially the Dantzig-Wolfe decomposition method determines the value of resources that are common to the various sub-problems. The process involves solving the sub-problems to determine the amount of the common resources that are used or supplied by the sub-problems at different price levels. The results of the sub-problems are then used to update the master or co-ordinating problem which is solved and the results used to determine the price of the resources that are common to the various sub-problems. The sequential solving of the sub-problems and the master continues in an iterative fashion until convergence to a global optimum is achieved. The decomposition method is described in Dantzig and Wolfe (1960) and Dantzig (1963) and a description of a parallel algorithm for solving Dantzig-Wolfe problems can be found in Ho and Loute (1981).

Although the Dantzig-Wolfe method of decomposition provides a solution to LP problems in a finite number of steps, various studies have shown that the efficiency of convergence to the optimum tends to be lower than for conventional solution methods (Alder and Ulkucu, 1973; Beale *et al*, 1965; Kutcher, 1973; Williams and Redwood, 1974). For this reason the Dantzig-Wolfe decomposition method has mainly been used for large scale problems that are not amenable to normal methods of solution. A point relating to the efficiency of the method is that the technique tends to be more efficient as the number of sub-problems becomes smaller (or for a particular problem as the individual sub-problems become larger) and when there are fewer links between the sub-problems. In the current model there are approximately 1.75 million lines of data input (see Figure 4-1 to Figure 4-4) and the size of this problem meant that decomposition techniques had to be considered if the model was to be solved.

Before discussing the approaches that were taken to solve the model it is useful to present an algebraic statement of the LP model. The standard form of a LP problem can be expressed as follows:

$$\text{minimise } \; z = c\,x, \tag{4-1}$$

$$\text{subject to } A\,x = b, \tag{4-2}$$

$$\text{and } \; x \geq 0 \tag{4-3}$$

where z is the objective function; c is a 1 * n vector of costs; x is the solution vector, A is a matrix with the dimensions m * n and is called the coefficient matrix; and b is an m * 1 vector and is commonly referred to as the right hand side vector.

This compares with a LP that is specified in the form of a Dantzig-Wolfe decomposition:

$$\text{minimise } z = \sum_{r=0}^{R} c_r\, x_r \tag{4-4}$$

$$\text{subject to } \sum_{r=0}^{R} A_r\, x_r = b_0 \tag{4-5}$$

$$B_r\, x_r = b_r,\; r = 1, \ldots, R \tag{4-6}$$

$$x_r \geq 0,\; r = 0, \ldots, R \tag{4-7}$$

where R is the number of sub-problems[9] that comprise the model and is the coefficient matrix associated with an individual sub-problem. Other variables are defined in Equations 4-1 to 4-3. In the above specification Equation 4-5 refers to the master problem while Equation 4-6 represents the various sub-problems.

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[9] In this study R corresponds to the number of regions.

4.2 Implementation.

A number of approaches to solving the model were tried. The first was an attempt to solve the sub-problems in parallel on the Cray T3D supercomputer at the Edinburgh Parallel Computing Centre[10] (EPCC). This involved the author writing approximately 1,000 lines of Fortran code linking this code to a generalised mathematical programming library (ERGOL, Edinburgh Research Group Optimisation Library). The ERGOL libraries are authored by J. Hall and K. McKinnon and the version used in this study consists of approximately 25,000 lines of Fortran. ERGOL was developed as part of an ongoing series of research projects into optimisation problems that is being conducted in the Mathematics Department at Edinburgh University. Of the various issues considered by Hall and McKinnon perhaps the most active research related to solving linear problems on parallel computers (Hall and McKinnon, 1996). Given the background to ERGOL and the availability of expertise in the Mathematics Department and the EPCC the author considered that this approach offered an excellent opportunity to work on parallel programs and to use the most powerful computer in Europe.

However, in spite of initial promise there were difficulties with the approach (Hall *pers. comm.*, 1996). Because the efficiency issues associated with Dantzig-Wolfe decomposition problems can be significant a decision was made to include the sub-problems in the model at the largest possible size[11]. With respect to the Cray T3D the memory limitations of the processing elements dictated that the model be divided into four sub-problems that represent the regions Kinloss, Mylnefield, Paisley and Wick. Each of these sub-problems contained approximately 65,000 activities and required 40

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[10] Although the Cray T3D is going through a constant process of upgrading at the time of this work the Cray T3D consisted of 320 processing elements (PE). Each of the PE's uses a DEC Alpha 21064 processor that runs at 150 MHz and supports 64 bit integer and 64 bit IEEE floating point operations. The peak performance of the T3D array was 48 Gflop per second. Each of the processors have 64 Mbyte of RAM, and the aggregate memory of the machine was 20 Gbytes. The various processing elements were arranged in a three dimensional torus, and each of the links to the PE's has the capacity to simultaneously transfer data at 300 Mbytes per second.

[11] During early experiments with the model, an attempt was made to solve the model by using the farm-types as the basis of the sub-problems. The formulation, therefore, contained 20 sub-problems consisting of 5 farm type models which were represented for each of 4 regions (see Figures 4.1 to 4.4). Although ERGOL successfully solved these sub-problems the efficiency of convergence was poor. On several occasions the problem was aborted after the sub-problems and master were solved more than 50 to 60 times. This compares with the same model achieving a global optimum after 12 to 15 iterations when it was formulated with 4 regional sub-problems. A further point was that although the farm-type sub-problems were on average only a fifth of the size of the regional sub-problems they only solved approximately 20 percent faster than the regional sub-problems. Please note these comparisons were performed on the SUN network using the serial solution algorithm.

Mbytes of memory to be solved. However, when attempts were made to optimise the sub-problems it was extremely difficult to obtain a solution and the numerical difficulties could not be resolved in the time frame of this study. (Hall *pers. comm.*, 1996). A decision was therefore made to run the model on a network of Sun computers that is situated in the Mathematics Department at Edinburgh University[12].

This network is comprised of 48 Sun computers that have varying processor and memory capacities. The majority of the machines on the network are for the private use of staff and researchers and can be accessed with the permission of the respective owners. The machines available for public use and which had adequate memory[13] and processing speeds to be used in this study are listed in Table 4-1.

Table 4-1. Sun Computers on the Maths network.

Description	Number of Machines	Processing Speed (MHz)	Random Access Memory (Mbytes)
Sparc5	1	75	48
Sparc5	3	75	32
Sparc2	1	65	32
Sparc IPX	1	50	32

Although the processor units on the Suns are slower than those on the Cray T3D a range of software packages is available on the Suns that were sufficiently robust to solve the model. The software package that was selected on the Suns was International Business Machines (IBM) Optimisation Subroutine Library (OSL) which like ERGOL is a library of mathematical optimisation routines. OSL is a widely available and flexible commercial package that has been developed over many years by IBM (IBM, 1993; McKinnon *pers. comm.*, 1995). Further, the design and functionality of ERGOL is strongly influenced by OSL so it was relatively straightforward to modify the Fortran code that was written for the Cray T3D so that it could be used on the Sun network. Indeed much of the code written for the Cray T3D supercomputer was initially tested on the Suns. A listing of the programs that were written to implement a Dantzig-Wolfe decomposition is presented in Appendix 12.

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[12] It is the authors hope that as the ERGOL libraries undergo further development that it will become possible to exploit the processing power of the Cray T3D.

[13] The listed machines are configured so that in addition to Random Access Memory (RAM) they can use virtual memory which is limited only by the size of hard disk. However, the use of virtual memory does have a detrimental effect on computer performance, so when possible it is better to use machines with sufficient RAM.

Two approaches to solving the model on the Suns were tried. The first was similar to that attempted on the Cray T3D where the model was solved as a parallel problem. As on the Cray T3D, therefore, each of the regional sub-problems (or in parallel computing terminology, the slave problems), and the master or co-ordinating problem were allocated to a computer processor. However, as mentioned above it was necessary to make alterations to the program that was written for the Cray T3D. These involved including conditional compilation statements so that parts of the code are compiled depending on the status of directives that specify whether the code was to be linked to ERGOL or OSL and whether the code was to run on the Suns or the Cray T3D. The compiler directives that relate to the type of machine were principally included to allow the code that controls the transfer of information between computer processors to reflect differences in the communication protocols that are used on the different platforms[14]. The inclusion of the conditional compilation statements presented advantages for managing the code that was written. In particular, fewer versions of the program needed to be maintained which simplified the process of updating and testing the program to be run on different machines and to be linked to different libraries of optimisation routines.

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[14] The PVM protocol for passing messages is used on both the Cray T3D and the SUN network, however, there are various differences between the implementations. For details of transferring code from a SUN network to the Cray T3D see Notes on Porting PVM Codes to the T3D, 1995. Booth, S., Simpson, A., and Brough, C., Edinburgh Parallel Computing Centre.

Figure 4-1. Structure of National level Model.

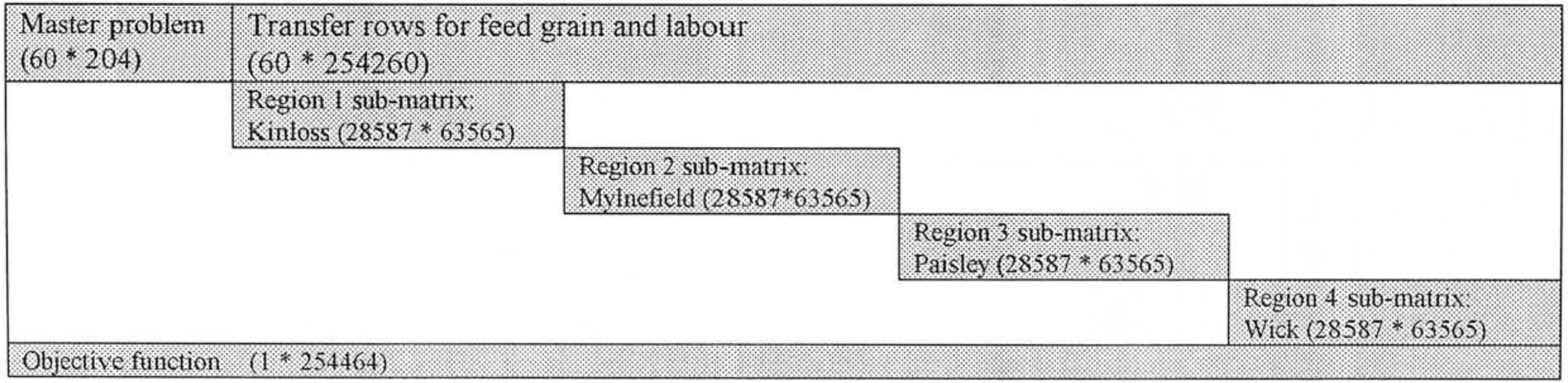


Figure 4-2. Structure of Regional Sub-matrix.

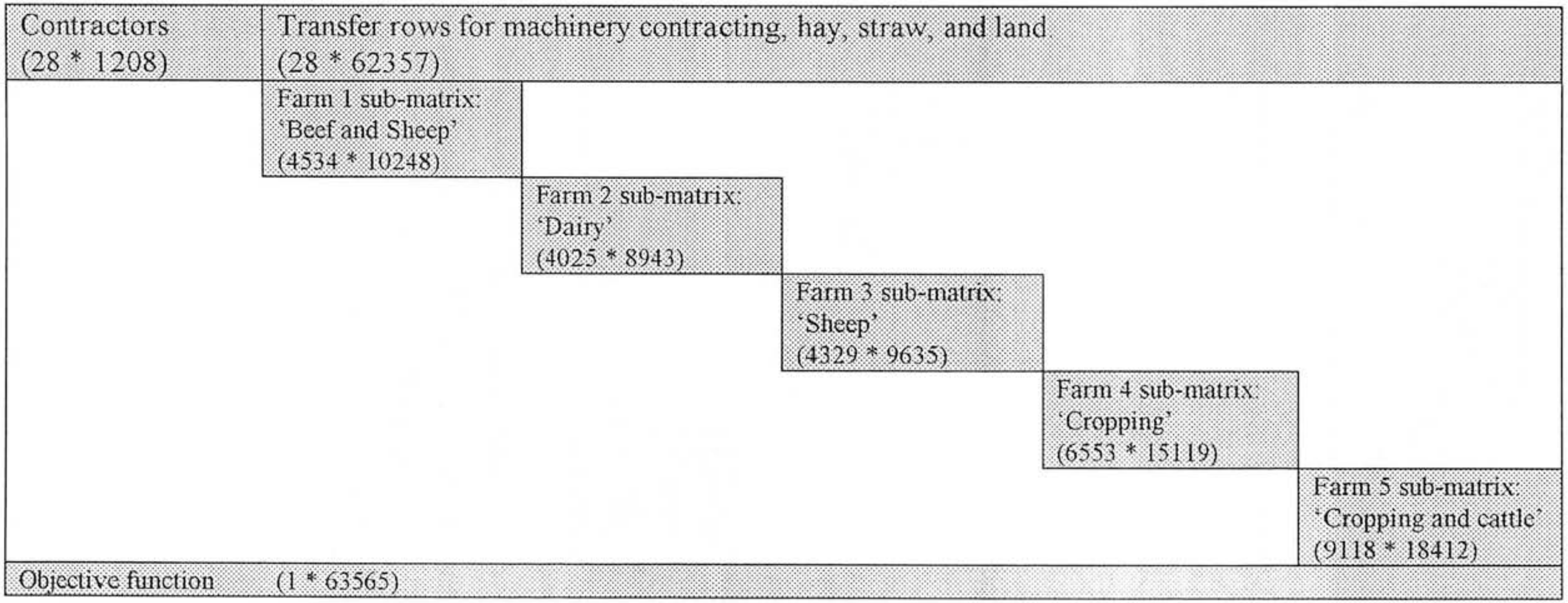


Figure 4-3. Structure of Farm Sub-matrix.

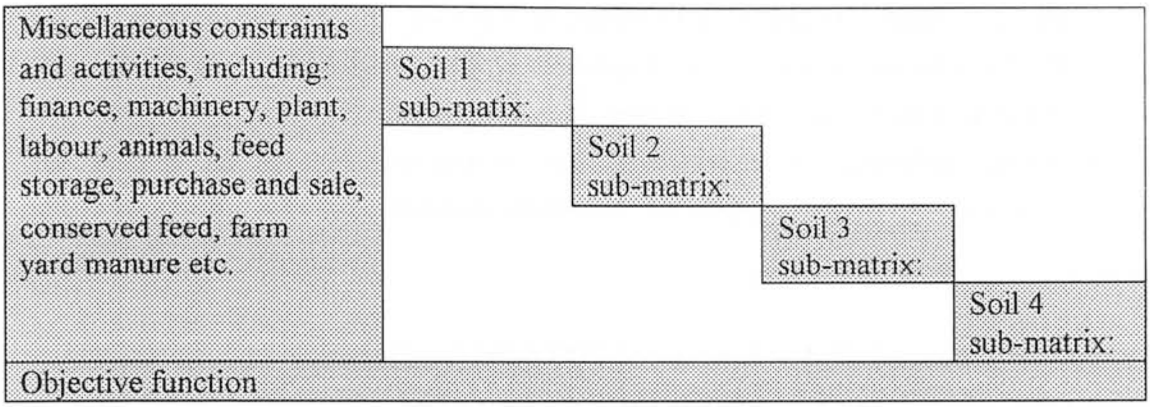
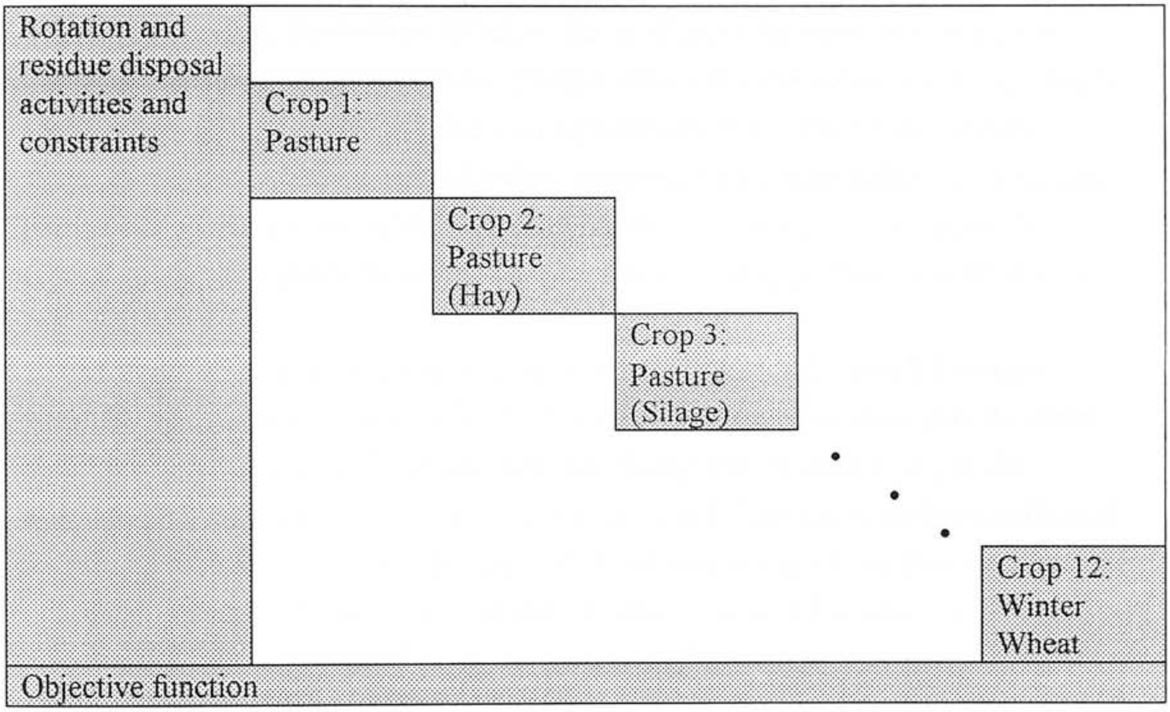


Figure 4-4. Structure of Soil Sub-matrix.



Because the regional sub-problems could be solved on the Suns, the parallel algorithm implemented on the Suns made greater progress towards a global solution than on the Cray T3D. However, the method was very demanding in terms of machine requirements. Although, there was an adequate number of machines on the Maths network that can be used to run the sub-problems the processing speed of the machines varied as did the memory and processing demands by other users. Unlike the Cray T3D where the various processors are identical and a single user has exclusive use of the processors during run time, the Maths network of Suns consists of a range of machines with differing memory and processor specifications. Also the processors on the Sun network can be simultaneously accessed by multiple users.

This meant that load imbalances tended to occur as one or more processors finish a task but then remain idle until the other processors have completed their respective tasks. While load imbalances occur on the Cray T3D the architecture of the Maths network meant that the problem was more serious on the Suns. Coupled to this the large memory requirement imposed on the different processors caused disruptions to other users of the network and often resulted in the program failing to terminate correctly.

The second approach to solving the model on the Suns was more successful. This involved formulating the solution algorithm so that the model could be solved as a serial problem. Although the method does not offer the potential speed advantages of a parallel algorithm, the method did allow the problem to be better matched to the available computing resources. These changes meant that the decomposition problem could be solved on a single machine with an appropriate amount of memory and processing speed. Although the difficulties associated with the parallel method meant that a detailed comparison of the serial and parallel algorithms was not possible, several conclusions about the relative performance of the approaches can be drawn.

Firstly the serial code was considerably more reliable than the parallel method. Also the improvement in the utilisation of computing resources meant that the serial algorithm was faster overall and caused fewer disruptions to other users of the network. It should be noted however that these conclusions are situation specific and might vary with factors such as the size of the problem being solved, the specifications of the computers on the network, and the pattern of demands by other users. If the memory and processing speed of the computers on the network was well balanced and the processing load had been lower, then the parallel algorithm would have performed better and may have out-performed the serial algorithm. From the above discussion, it can be seen that the problem presented in this study stressed the ability of both software and hardware resources. However, given the computing facilities that were available the serial solution method was found to be robust and produced acceptable solution times. The experiments reported in Chapter 9 were all performed using the serial algorithm on a Sparc5 machine operating at 75 MHz and with 48 Mbytes of memory.

5. CROP AND PASTURE MODELS.

5.1 Introduction.

The types of adjustments to climate change that occur at the farm level will depend on the actual changes in climate that eventuate. If the climate changes by a small amount, the impact on Scottish farming systems may also be small (Parry, 1985; Parry and Carter, 1985; Parry *et al*, 1989; Rowntree *et al*, 1989). For example, farmers may continue to plant the same types of crops that they have grown in the past, but find that it is necessary to alter the timing of planting or to introduce new cultivars that have thermal and moisture requirements that are better suited to the changed environment. However, if the change in climate is greater than the capacity of minor adjustments to contend with such change, farmers responses will also need to be greater. Crops not currently grown in Scotland, may be introduced as prevailing climatic conditions become less suited to traditional crops. Another adjustment that is likely to occur, both within and between farms, is for the balance between livestock and cropping enterprises to change (Goudrian *et al*, 1990; Hillel and Rosenzweig, 1989). Changes of this type may have a significant impact on the country side and rural infrastructure. The LP model has been structured to allow changes in land use and production levels, that result from an altered climate, to be considered.

It is assumed that the primary impacts of a change in climate are on the productivity of arable and forage crops and on the availability of machinery working hours (Carter *et al*, 1988; Cooper and McGechan, 1994 and 1996; Parry and Carter, 1990; Topp and Doyle, 1996a). In the agriculture sector model, weather is not explicitly modelled, but rather an attempt is made to simplify the cascade of biological and physical effects that arise from a change in climate, by expressing the influence of variations in climate in terms of the impacts that these exert on the potential production of crops. It is important, therefore, to accurately estimate the sensitivity of crops and pasture to climatic factors, if the implications of a changing climate to Scottish farming systems are to be satisfactorily assessed.

The LP models of crop and pasture production are formulated as relatively simple models of growth that are responsive to a selected set of management variables. The majority of parameter values are estimated from synthetic time series data using a similar approach to that used to parametise the animal models (see Chapter 6). But unlike the animal models where a single set of parameters are estimated for a relatively wide range of conditions, the derived crop parameters are specific to each of the climates, regions, soils and management variables that are considered.

The crops and management variables that are included, are selected on the basis that they are representative of the types of crops and actions available to farmers as they adjust to changing environmental conditions. The crop management variables that are present in the model range from factors that have a relatively minor effect on farming practices to ones that have a fundamental impact which can result in significant changes in land use. The farm level adjustments in cropping systems that can be evaluated with the LP model include changes in (1) the mix of crops that are grown on farms; (2) the cropping rotation; (3) rates of fertiliser use; (4) method of crop residue disposal; (5) level of pesticide use; (6) the timing of operations such as tillage and planting; and (7) changes in the machinery complement required by farms. A summary of the crop and pasture sub-matrices can be found in Figure 5-1 and Figure 5-2.

Two areas where shortcomings in current methodologies were identified relate to (1) the representation of crop rotations and (2) the modelling of weeds. As the number of crops included in a model increases, the number of rotations that may result quickly becomes very large, particularly as the length of time horizon that is considered increases. For this reason, LP studies that explicitly consider the influence of alternative sequences of crops, tend to include either just a few crops for a small number of years, or a restricted set of specified rotations (see for example Pannell and Panetta, 1986). In this study it was desirable to establish a procedure that generated a more general solution than those produced using existing methodologies. A formulation that overcomes many of the difficulties of existing approaches is presented. Also a methodology that allows the growth and death of weeds to be explicitly represented in the model has been developed.

The crop management variables that are included in the LP model are presented in Section 5.2.1. The LP models of crop and pasture growth and the implications of the selected model structure are described in Section 5.2.2 and a methodology that relates to the modelling of weeds and pests is presented in Section 5.2.3. The cycling of crop nitrogen, crop rotations and issues associated with crop residue disposal are discussed

Figure 5-1. Arable Crop Sub-matrix[15].

	Crop	Crop Growth	Harvest Grain	Store Grain	Sell Grain	Purchase Grain	Soil Nitrogen	Apply Fertiliser	Purchase Fertiliser
Crop Yield Reconciliation	-A -A -A[16] -A -A -A -A -A -A	1 [17] 1 1							
Crop Yield		[18] -1 -1 -1	[19] 1						
Grain Reconciliation			-1 [20]	1 [21] -A 1 -A 1	1 [22] 1 1	-1 [23] -1 -1			
Machinery Labour, and Plant	A A A[24] A A A		A [25]	A [26] A A				A [27]	
Soil Nitrogen	-A -A -A[28] -A -A -A -A -A -A	A[29] -A[30] A -A A					1 [31] -A 1 -A 1	-1 [32]	
Permit Fertiliser	[33] -A -A -A							[34] 1	
Fertiliser								1 [35]	-1 [36]

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[15] 'A' refers to non-zero coefficients that are not equal to unity. Following the conventions of Dent et al (1986) a negative element supplies permission or resources while a positive element signifies the uptake of permission or resource.

[16] Potential crop growth (see μ in Equation 5-1).

[17] Actual crop growth (see Γ in Equation 5-1).

[18] Sum crop growth or yield.

[19] Harvest grain from field.

[20] Harvested grain is made available for storage or sale.

[21] Inter-period transfers of stored grain (see Dent et al, 1986).

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[22] Sell grain.
[23] Purchase grain.
[24] Machinery, plant and labour requirements for cultivation and planting operations.
[25] Machinery, plant and labour requirements for harvesting operations.
[26] Machinery, plant and labour requirements for storing grain.
[27] Machinery, plant and labour requirements for applying fertiliser.
[28] Soil nitrogen that is derived from fixation, atmospheric deposition and mineralisation (see $\gamma\eta$, in Equation 5-17).
[29] Nitrogen taken up by growing crop (see a1 in Equation 5-16).
[30] Nitrogen leached from crop material (see a19 in Equation 5-16).
[31] Inter-period transfers of soil nitrogen (see a14 in Equation 5-14).
[32] Increment to soil nitrogen associated with fertiliser application (see f in Equation 5-14).
[33] Maximum permitted fertiliser application (see Appendix 5).
[34] Utilise permission to apply fertiliser.
[35] Apply fertiliser.
[36] Purchase fertiliser.

Figure 5-2. Pasture Sub-matrix[37].

	Pasture	Pasture Growth	Pasture Dry Matter	Graze Pasture	Conserve Forage	Store Forage	Purchase Forage	Sell Forage
Pasture Growth Reconciliation	-A -A -A[38] -A -A -A -A -A -A	1 [39] 1 1						
Pasture Dry Matter		-1 -1 -1	1 [40] -A 1 -A 1	1 [41] 1 1	[42] 1			
Conserved Feed					[43] -1	1 [44] -A 1 -A 1	-1 [45] -1 -1	1 [46] 1 1
Machinery Labour, and Plant	A A A[46] A A A A A A			A [47] A A		A [48] A A		
Soil Nitrogen	-A -A -A[49] -A -A -A -A -A -A	A [50] A A	-A[51] -A -A	-A[52] -A -A				

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[37] 'A' refers to non-zero coefficients that are not equal to unity.

[38] Potential pasture growth (see a2 in Equation 5-3).

[39] Actual pasture growth (see Equation 5-3).

[40] Inter-period transfers of pasture dry matter (see a5 in Equation 5-3).

[41] Removal of pasture from field by grazing animals (see I in Equation 5-3).

[42] Removal of pasture from field by conservation operations (see FH in Equation 5-3).

[43] Supply conserved forage.

[44] Inter-period transfers of conserved forage.

[45] Purchase conserved forage.

[46] Sell conserved forage.

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[47] Machinery, plant and labour requirements for cultivation, planting and maintenance operations.
[48] Labour requirements associated with grazing animals.
[49] Machinery, plant and labour requirements associated with forage storage.
[50] Soil Nitrogen that is derived from fixation, atmospheric deposition and mineralisation (see $\gamma\eta$ in Equation 5-17).
[51] Nitrogen taken up by growing pasture (see a1 in Equation 5-16).
[52] Nitrogen leached from dead pasture material (see a19 in Equation 5-16).
[53] Nitrogen leached from dead pasture material (see a19 in Equation 5-16).

in Sections 5.2.4 to 5.2.6, respectively. In Section 5.3, the estimation of the model parameters is presented; the simulation models that are used and their suitability is discussed.

5.2 Model Structure.

5.2.1 Crop Management.

A relatively large number of crop types are represented in the farm models. These include grass and grass / clover swards, swedes, vining peas, potatoes, winter oilseed rape, spring and winter barley, and winter wheat (see Table 5-1). The selected crops represent a significant proportion of the economically important crops that are grown in Scotland and which are likely to continue to be of consequence in the future (MacKerron *pers. comm.,* 1995). One crop that arguably could have been included, but for reasons of simplicity is not, is maize for grain. Although maize is not currently grown in Scotland, it may become an economically viable crop (Doyle *pers. comm.,* 1995) if climate changes of the magnitude postulated for a doubling of atmospheric carbon dioxide occur (Peiris *et al,* 1996). By excluding maize the model may overstate the deleterious effects or understate the beneficial effects of a change in climate. However, unless maize was to become a major crop under an altered climate, it is unlikely that this would cause significant errors.

An assumption in the study is that pasture and animal feed crops can be grown on all of the modelled soils, while crops grown for human consumption can only be planted on the two most productive or heaviest of the represented soil types (see Table 5-1). This assumption is adopted, as farmers tend to produce high value crops on their best land. However, as discussed in the section relating to the farm typology (see Section 3.2.1), the method that is used to specify the characteristics of soils incompletely captures all of the variables that are likely to affect soil productivity. By restricting high value crops from being planted on lighter soils an effort is made to restrict these crops from being sown on unsuitable land. With the data available to the current study, it is not possible to evaluate the appropriateness of this restriction. However, if improved data becomes available, a more closely defined typology could be implemented that would better represent factors that influence the suitability of soils for different crops.

Table 5-1. Modelled Crops.

Crop	Soils on which crops modelled	Response to nitrogen modelled	Weeds and response to pesticides modelled	Farm Types on which crops are modelled	Planting Dates	Harvest Dates
1: Grass	1 - 4	Yes	No	1 - 3, 5	as per undersown spring feed barley	March - October
2: Grass / Clover	1 - 4	Yes	No	1 - 3, 5	as per undersown spring feed barley	March - October
3: Swedes	1 - 4	No	No	1, 3	May	December - January
4: Potatoes	3 - 4	No	No	4, 5	March, April, May	September
5: Spring Feed Barley	1 - 4	Yes	Yes	4, 5	March, April, May	September
6: Spring Feed Barley (under sown with pasture)	1 - 4	Yes	Yes	5	March, April, May	September
7: Vining Peas	3 - 4	No	No	4, 5	March, April, May	September
8: Winter Oilseed Rape	3 - 4	Yes	No	4, 5	July, August, September	August
9: Winter Feed Barley	1 - 4	Yes	Yes	4, 5	September, October, November	August
10: Winter Malting Barley	3 - 4	Yes	No	4, 5	September, October, November	August
11: Winter Feed Wheat	1 - 4	Yes	Yes	4, 5	October, November, December	September
12: Winter Milling Wheat	3 - 4	Yes	No	4, 5	October, November, December	September

Management decisions relating to crop husbandry are uniquely defined for the various combinations of soil type, crop cultivar, and cultivation timings represented in the model. A listing of the machinery operations that are performed on the various crops is presented in Appendix 5. The majority of crops that are included in the LP model can be planted on one of three possible planting dates[54]. In contrast, only a single harvest date for each of the crops is specified. It would be possible to alter the models formulation to consider the influence of alternate harvest dates on factors such as crop yield, machinery requirements and the sequencing of crop harvesting. However, a difficulty associated with varying the date of harvesting relates to the estimation of suitable yield loss functions as not all of the simulation models that are used to estimate crop yield consider changes in yield following crop maturity. It is beyond the scope of the current project to estimate the likely implications to yield of harvesting at sub-optimal times. If acceptable estimates of these losses are obtained, the model could be readily extended to evaluate such changes on the profitability of the represented farming systems.

The crop rotational restrictions that are included are as follows: vining peas may be planted only once every six years to the same ground; potatoes once every four years; and rape once every six years. Grass and grass / clover swards must be ploughed after a minimum of three years and before a maximum of 8 years. Further, it is assumed that the ploughing of pasture influences the rate of nitrogen mineralisation in the first two crops following pasture. Also, on farms that grow crops, pasture can only be established by undersowing spring feed barley. On farm types that do not involve cropping activities, pasture is established by conventional cultivation. Some other constraints are that winter sown barley and pasture are the only crops that can precede rape. If the crop preceding rape is winter barley, the rape crop must be planted in September. The timing of sowing winter barley may be restricted, depending on the harvest date of the preceding crop. The earliest that winter barley can be sown is delayed by a month, until October, if the preceding crop is one of the following: peas, potatoes, spring sown barley, or winter wheat (see Figure 5-3).

The method of crop residue disposal has implications for soil nutrient cycling, machinery and labour requirements, and weed and pest populations (Audsley, 1984; Cussans *et al*, 1987). For the majority of cereal crops the model determines the means

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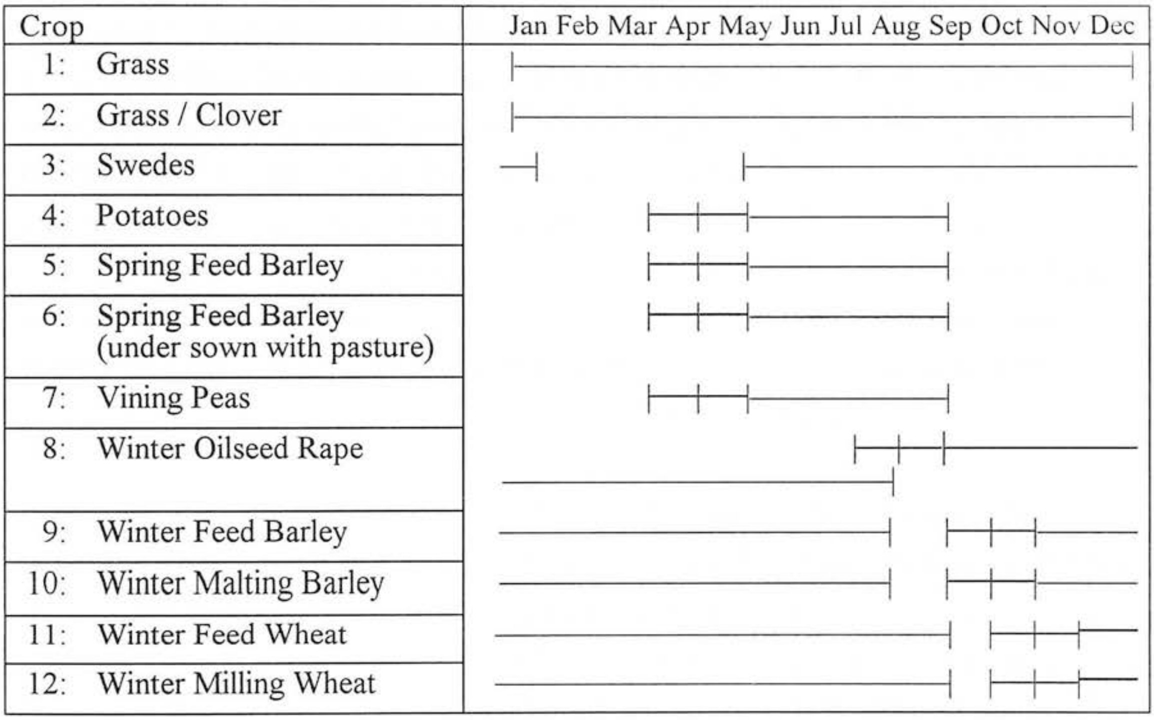
[54] An exception to this is swedes, where only a single sowing date is considered as suitable estimates of likely changes in crop growth with changes in planting date were not available.

(soil incorporation, or baling as straw) and timing of residue disposal. For other crops, the method by which residues are disposed is restricted for management reasons; these include baling of under-sown spring barley residues, grazing of pea straw if animals are available, or incorporation if no animals are present, and incorporation of rape and potato residues. The method used to model residue disposal, and the integration of these activities with crop rotations and the implications that residue disposal may have on the planting of an incoming crop is discussed in Section 5.2.6.

Figure 5-3. Period that Crops Grow in Field.



For the majority of crops, farm yard manure (FYM) is applied in the month of cultivation. The model selects whether to apply farm yard manure, and subject to a maximum limit, the amount that is applied. Inorganic fertiliser is applied at the time of crop establishment either by broadcasting or drilling, or later in the growing season by broadcasting. In the case of potatoes, vining peas and swedes, nitrogen is not explicitly modelled; the constraints that relate to the application of fertiliser and FYM are therefore specified differently to other crops. For these crops the rates of fertiliser and FYM applications are required to equal the maximum amounts permitted. It should be noted that on farms where there are no animals, applications of farm yard manure are zero.

The machinery operations that are necessary to establish, maintain, and harvest crops are specified for each crop and planting date. The majority of crops are established by a combination of ploughing, power harrowing, harrowing, rolling and planting. For potatoes, crop establishment also involves rotovating, ridging and passes with a stone clod separator and a stone clod windrower. The timing of operations are specific to the planting date of the crop and are dependent on the method of residue disposal employed for the preceding crop. Discussion relating to the influence of weather on the requirements for machinery and labour can be found in Section 7.1.1.

Machinery operations performed on crops that are growing in the field include spraying, fertiliser broadcasting, and in the case of potatoes, irrigation. With regard to spraying, it is assumed that biocides are applied at variable rates to crop cultivars that are used for feed (refer to Table 5-1). This is in contrast to crops destined for end uses other than animal feed which are subjected to prophylactic spraying regimes at locally recommended rates. For these crops it is assumed that the maintenance of yield and grain quality factors, such as weed contamination and insect and disease damage, will dominate economic decisions relating to chemical dose rates (Cousens, 1986). The crop spray program is presented in Table 5-2 and Appendix 9.

Pasture may be grazed by animals or harvested as hay or silage. Pasture that is conserved in the form of hay may be sold or stored and fed to animals at a future time; silage may similarly be stored for subsequent utilisation but there is no provision for silage to be sold. Requirements for machinery, storage and labour that arise as a result of pasture conservation are specified for each of the respective operations. The marketing options that are available for harvested crop products are specified for each crop. All crop produce can be stored for a model determined length of time, except vining peas which leave the farm at harvest, and sold. In addition, suitable varieties may be purchased or retained on the farm and fed to animals or used as seed in subsequent crops. The methodology used in the model to represent selling and purchase activities and the storage of physical product is described by Dent *et al* (1986).

Table 5-2. Crop Spray Program[55].

Crop	Chemicals	Month of Application	Expected Number of Applications	Application Rate (kg a.i. hectare^{-1})
3: Swedes	trifluralin (H)	May	1.0	2.30
4: Potatoes	paraquat (H)	May	1.0	3.00
	mancozeb & metalaxyl (F)	June	2.0	2.00
	pirimicarb (I)	June	0.1	0.28
	mancozeb & metalaxyl (F)	July	3.0	2.00
	fentin hydroxide (F)	August	2.0	0.56
5, 6: Spring Feed Barley and Undersown Spring Feed Barley	fenpropimorph (F)	May	1.0	1.00
	manganese sulphate (F)	May	0.5	6.00
	mecoprop & metsulfuron-methyl (H)	May	1.0	2.00
	fenpropimorph (F)	June	1.0	1.00
	pirimicarb (I)	June	0.1	0.28
7: Vining Peas	terbuthylazine & terbutyn (H)	May	1.0	3.40
	iprodione (F)	June	2.0	2.00
8: Winter Oilseed Rape	metazachlor (H)	October	1.0	2.50
	quizalofop-ethyl (H)	October	1.0	0.15
	carbendazim (F)	November	1.0	1.00
	prochloraz (F)	November	1.0	1.10
	iprodione (F)	May	1.0	2.00
9, 10: Winter Feed Barley and Winter Malting Barley	linuron & trifluralin (H)	Month of planting	1.0	4.00
	tridemorph (F)	November	1.0	0.70
	fenpropimorph (F)	March	1.0	1.00
	mecoprop & metsulfuron-methyl (H)	March	1.0	2.00
	fenpropimorph (F)	May	1.0	1.00
	pirimicarb (I)	June	0.5	0.28
11, 12: Winter Feed Wheat and Winter Milling Wheat	linuron & trifluralin (H)	Month of planting	1.0	4.00
	mecoprop & metsulfuron-methyl (H)	March	1.0	2.00
	prochloraz (F)	April	1.0	0.70
	triademenol, tridemorph, & chlormequat (F)	May	1.0	1.00
	pirimicarb (I)	June	0.2	0.28
	propiconazole (F)	June	2.0	0.50

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[55] F = Fungicide, H = Herbicide, I = Insecticide, a.i. = active ingredient.

5.2.2 Crop and Pasture Growth.

The equations that represent crop and pasture growth are presented in this section. Growth of arable crops is modelled, using a monthly time step, in terms of change in harvestable yield. It is assumed that crop growth is subject to a limit on potential growth and the availability of soil nitrogen. A basal level in the potential yield of arable crops is specified for each cultivar and time of planting. In addition, the potential yield of crops is assumed to vary with applications of pesticides, and for crops grown to produce animal feed, to vary with the presence of weeds. For arable crops, applications of pesticides, excluding herbicides on crops grown for animal feed, are assumed to affect the objective function by increasing potential crop yield. This approach is theoretically weaker than modelling the impact that pesticides exert on crop yield by reducing pest populations (see Section 5.2.3 on weed growth), but is adopted for reasons of simplicity.

Arable crop yield (Γ, kg DM) is calculated as the sum of growth occurring in the various months and is defined as:

$$\Gamma_{t,c} = \min\left(\mu_{t,c}, \frac{\eta_{t,c}}{a1_{t,c}}\right) \qquad (5\text{-}1)$$

$$\mu_{t,c} = a2_{t,c} + a3_{t,c,m} P_{t,c,m} - a4_c \, \omega_{t,c} \qquad (5\text{-}2)$$

where μ is the potential increment in harvestable crop yield; t is the integration step (months); c is the type of crop; η is soil nitrogen (kg); a1 is the amount of nitrogen taken up by the plant per unit of harvestable crop yield; a2 is a basal limit to potential yield increment; P is the level of pest control measure m that is applied to the crop; a3 is the contribution to potential yield per unit of P; ω is the amount of weed material present in the crop; and a4 is the reduction in potential crop yield associated with competition between weeds and the growing crop for light and moisture. The estimates of the parameters in Equations 5-1 and 5-2 are presented in Table 5-10, Table 5-14, Table 5-16, and Appendices 6 and 7.

With the exception of vining peas, potatoes and swedes, the availability of soil nitrogen is assumed to constrain the yield of arable crops to be less than or equal to the estimates of potential yield. In the case of potatoes, an assumption of the study is that the high profit margin associated with the crop when it is grown in appropriate conditions, means that farmers will fertilise sufficiently heavily so that soil nutrients do not limit crop yield. In the case of vining peas, farmers do not normally apply fertiliser nitrogen, as peas are a leguminous plant (Barton *pers. comm.*, 1995). For swedes, a lack of suitable data, meant that it is inappropriate to develop a detailed model of this crop. The nitrogen cycle associated with vining peas and swedes is not therefore represented in the LP model (see Table 5-1).

With respect to arable crops, the study is primarily interested in modelling changes in yield at harvest. This contrasts with pasture where the quantity of dry matter occurring in a field during a particular month may vary with alternate management regimes and hence influence production in subsequent time periods (Christian *et al*, 1978) and also the amount of forage intake that can be achieved by animals (Elsen *et al*, 1988; Gibb and Treacher, 1978; Hughes *et al*, 1980; McCall *et al*, 1986; White, 1975). The model provides a monthly reconciliation of the amount of pasture in each of the regions, farms, soils and pasture types that are represented. The quantity of pasture is reconciled for each of three different methods of forage conservation. These include pasture which is only available for grazing, pasture that can be grazed or harvested for hay, and pasture that is grazed or conserved for silage (for further discussion, see Section 5.3.1).

In the current context, pasture material is defined as the amount of green leaf in the sward. The reasons for selecting this variable as a predictor of the amount of pasture are as follows. If the amounts of leaf, stem and dead material are each represented separately as in Topp and Doyle's (1996a) simulation model, the LP model would need to be formulated so that the death of leaf and stem material, and the subsequent decay of dead material is accounted for. While this information would allow the selective grazing by animals of the various pasture constituents to be represented, this would necessitate a considerably more complex formulation than is included in the current model. It would be difficult to justify the inclusion of this detail when the level of spatial and temporal aggregation of other variables in the LP model is considered.

A further point is that as leaf material is grazed in preference to stem and dead material by animals (Christian *et al*, 1978; Geenty and Sykes, 1982; Hamilton *et al*, 1973; Jamieson and Hodgson, 1979; Zemmelink, 1980), leaf represents a greater proportion of the animals diet than its abundance in a sward would suggest. The amount of leaf that is present in a pasture, therefore, provides a predictor of a significant component of intake by grazing animals. It should be noted that estimates of the amount of energy intake achieved by grazing animals are adjusted to reflect the mean proportion of pasture intake that is derived from stem and dead material; that is the energy contained in stem and dead material is attributed to ingested leaf material.

Another reason that leaf was selected as an estimator of the amount of pasture, is related to the fact that leaf material is photosynthetically active. It was thought that variations in the amount of leaf would, therefore, provide some explanation of changes in the growth of pasture. When the model was tested, however, the amount of leaf in the sward appeared to have little impact when predicting variations in pasture growth. A possible reason for this lack of sensitivity may be related to the level of temporal and spatial aggregation of the LP models of pasture growth.

The actual growth of pasture is assumed to be the minimum of a basal limit to potential growth and a limit based on the availability of mineral nitrogen, such that:

$$K_{t,c} = (1-a5_{t,c})\, K_{t-1,c} + \min\left(a2_{t,c}, \frac{\eta_{t,c}}{a1_{t,c}}\right) - I_{t,c} - FH_{t,c} \quad (5\text{-}3)$$

where K is the amount of leaf material present in the field (kg DM); a5 represents losses associated with death and decay of pasture; I is animal intake (see Equations 6-7 and 6-8); and FH is mechanical harvesting for forage. The parameters a1 and a2 are defined in Equations 5-1 and 5-2; a5 is estimated from the time series data of Topp and Doyle (1994) (see Table 5-4).

The amount of pasture that is available to be harvested either mechanically or by animals is assumed to be the difference between the amount of pasture that is present and a limit that represents the amount of dry matter that must remain after cutting or grazing. For further discussion of this point see Section 6.2.3.3. The requirements for machinery and subsequent storage and feeding of conserved forage are discussed in Section 7.1.

5.2.3 Weeds and Pests.

The incidence of weeds and pests is likely to be considerably influenced by changes in climatic factors (MacKerron *et al*, 1993). However, the methods used to study weed and pest growth, in linear programming studies, have not been well developed as activities that represent weed or pest growth do not enter linear programming solutions on the basis of aspects beneficial to the farm plan (Finlayson and McGregor, 1992). To avoid this difficulty, previous studies have often assumed that pest control measures act by increasing crop yields, rather than by destroying the pests that reduce crop yield. This simplification has meant that weed and pest growth do not have to be explicitly represented in the model structure, but also means that bias can enter the analysis (Lichtenberg and Zilberman, 1986). The method that is presented logically constrains weed growth to occur, subject to the presence of soil nutrients and a photosynthetic growth limit, so that the effects of weeds on crop growth and other aspects of crop production can be better addressed. Although this technique was initially developed to study weeds, the method could be readily extended to studies of the incidence of other pests and diseases.

The relationship between weeds and losses in feed production in pasture are complex. Although weeds tend to be less palatable and productive than grass or clover that are displaced from a sward, weeds may have some feeding value for ruminants. In contrast, other weeds can be toxic if ingested by grazing animals. The dynamics of weed populations in perennial pastures also tend to be more complicated than in arable crops. Annual weeds tend to predominate in cropping rotations where the soil is cultivated each year. However, under pasture a soil may remain undisturbed for a number of years so that biennial and perennial weeds become a problem. In the current study, it is not possible to satisfactorily address issues relating to weed dynamics that extend beyond the single year time horizon of the LP model. For this reason weeds and other pests and diseases and applications of pesticides are not modelled in pasture.

In crops where weeds are represented (see Table 5-1), the method of specifying weed growth assumes a basal limit to potential growth that varies as a function of the quantity of weed dry matter present in the field. Weed growth indirectly affects crop growth by reducing the pool of available nitrogen. Reductions in modelled crop yield that result from weeds competing for available light and moisture (Zimdahl, 1980), are addressed by reducing potential crop growth inversely with the quantity of weed dry matter present (see Equation 5-2).

Chemical and mechanical control measures can significantly influence the amount of photosynthetically active weed material present in a given period, and hence the rate of weed growth in subsequent periods. For this reason, the potential growth limits associated with weeds vary with the time of year and as a multiplicative function of the respective amount of dry matter transferred from the previous period. In the current model it is assumed that management actions undertaken to control weeds in a crop, at any given point in time, will be performed on all land that is planted to the crop. The impact of a weed control measure should, therefore, influence growth of weeds in subsequent periods for the entire area that is devoted to the crop.

Although alternate regimes of mechanical and animal harvesting of pasture can lead to different levels of accumulation of pasture in a field, a relationship between the amount of pasture and rates of pasture growth is not included in the LP model. The reason for this is related to the procedure used to estimate parameters for the LP model. The estimation of parameters involved aggregating time series data, across 12 different fields that are represented in Topp and Doyle's (1994) time series data. Pasture growth on fields that have been recently cut is therefore averaged with other fields that may not have been harvested for some time. Due to non-linearities in the growth pattern of pasture with increasing amounts of dry matter in a field (Topp and Doyle, 1994), this procedure did not produce satisfactory estimates of the contribution of photosynthetic material to subsequent rates of pasture growth. As weeds are not modelled as an aggregate of fields that are each subjected to differential management, the LP estimates of weed growth should avoid the difficulties associated with modelling pasture growth.

In the current model, weed growth is logically constrained to occur, subject to the presence of soil nutrients and a photosynthetic growth limit, so that the effects of weeds on crop growth and other aspects of crop production is explicitly addressed. The method used to represent weed growth was originally developed as part of a mixed integer linear programming (MILP) model (see Finlayson and McGregor, 1992), however, the subsequent formulation of the model as a D-W decomposition has precluded the use of integer variables (see Chapter 4). It was necessary, therefore, to linearise the specification of weed growth. In the following section, both the MILP and the LP formulations are presented, along with a discussion of the implications of the alternative formulations for the generality of the resulting model solutions. A summary of the weed growth sub-matrix is presented in Figure 5-4.

Figure 5-4. Weed Growth Sub-matrix[56].

	Crop	Crop Growth	Weeds	Weed Growth	Apply Herbicide	Apply Pesticide
Potential Crop Yield	-A -A -A[57] -A -A -A -A -A -A	1 [58] 1 1	A [59] A A			[60] -A -A -A
Weeds			1 [61] -A 1 -A 1	-1 [62] -1 -1	[63] A A	
Permit Weed Growth	-A -A -A[64] -A -A -A -A -A -A		-A[65] -A -A	1 [66] 1 1		
Soil Nitrogen		A [67] A A	-A[68] -A -A	A [69] A A	-A -A[70]	
Permit Herbicide	[71] -A -A -A				[72] 1 1	
Permit Pesticide	[73] -A -A -A					[74] 1 1 1

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[56] 'A' refers to non-zero coefficients that are not equal to unity.

[57] Potential crop growth (see μ in Equation 5-1).

[58] Actual crop growth (see Γ in Equation 5-1).

[59] Reduction in potential crop yield associated with competition between weeds and the growing crop for light and moisture (see a4 in Equation 5-2).

[60] Contribution to potential crop yield associated with pesticide applications (see a3 in Equation 5-2).

[61] Inter-period transfers of weed material (see a5 in Equation 5-4).

[62] Increment to weed material in field (see $\Delta\omega$ in Equation 5-4).

[63] Reduction in weed material associatied with application of herbicide (see $c\omega$ in Equation 5-4).

[64] Potential weed growth associated with weed seed and root reserves (see a6 in Equation 5-5).

[65] Increment to potential weed growth associated with photosynthesis (see a7 in Equation 5-5).

[66] Actual growth of weed material (see $\Delta\omega$ in Equation 5-4).

[67] Nitrogen taken up by growing crop (see a1 in Equation 5-16).

[68] Nitrogen leached from dead weed material (see a18 in Equation 5-15).

[69] Nitrogen taken up by growing weeds (see a17 in Equation 5-15).

[70] Nitrogen leached from dead weed material (see a18 in Equation 5-15).

[71] Maximum amount of herbicide that can be applied to crop (see H in Equation 5-6).

[72] Actual herbicide application (see Equation 5-6).

[73] Maximum amount of fungicide or insecticide that can be applied to crop (see Equation 5-13).

[74] Actual fungicide or insecticide application (see Equation 5-6).

With regard to the MILP formulation, variables representing weed growth, enter the farm plan at appropriate levels due to the presence of integer variables that ensure slack weed growth can only occur if soil nitrogen is unavailable either for uptake by weeds or to be transferred to subsequent periods. When soil nitrogen is present in sufficient quantities to be transferred to the following period, then actual weed growth equals potential weed growth. The adopted structure has the effect of forcing weed growth to occur at potential rates, when adequate reserves of soil nutrients are present. In situations where soil nitrogen is limiting, growth will occur at less than the potential rate, but all available nitrogen is then taken up by weeds.

The method provides a simple representation of competition for nutrients between crops and weeds. In the model, crops tend to take up nutrients ahead of weeds due to the formulation of the objective function. However, to partition nutrients between crops and weeds, on the basis of their respective competitive abilities, a pieci-linear approximation of the relative uptake rates of nutrients at differing availability's would need to be specified and additional data and integer variables would be required.

The amount of weed material present in a given actively growing crop can be described by a vector ω (kg DM).

$$\omega_{t,c} = (1 - a5_{t,c})\,\omega_{t-1,c} + \Delta\omega_{t,c} - c\omega_{t,c,m} \qquad (5\text{-}4)$$

where a5 is the fraction of material that is lost when weeds are transferred from the preceding to the current time period and reflects normal processes of death and decay; $\Delta\omega$ is growth of weed matter (kg DM) and $c\omega$ is the death and decay of weed matter (kg DM) associated with control measure m.

The growth of weeds is described as follows:

$$\Delta\omega_{t,c} = a6_{t} + a7_{t-1}\,\omega_{t-1,c} - s\omega_{t,c} \qquad (5\text{-}5)$$

where a6 is the potential growth limit associated with weed seed and root reserves (kg DM); a7 is the increment to potential weed growth per kilogram of weed matter (kg DM kg DM^{-1}) and represents variations in potential growth with changes in the level of photosynthetically active weed matter present in the field; $s\omega$ is unfulfilled potential weed growth (kg DM), and assumes a positive value, that satisfies the equality constraint, when insufficient soil nitrogen is available for weed growth to occur at potential rates.

The amount of weed material that ($c\omega$, kg) dies as a result of an application of herbicide is assumed to be a function of the amount of herbicide applied and the efficacy of the herbicide.

$$c\omega_{t,c,m} = a8_{t,c,m} H_{t,c,m} \tag{5-6}$$

where a8 is the amount of green weeds to die per unit of active ingredient of herbicide; and H is the amount of herbicide that is applied (kg a.i.). The parameter estimates in Equations 5-5 to 5-7 can be found in Table 5-4, Table 5-13, Table 5-14 and Table 5-15.

To ensure that slack weed growth only occurs when all available soil nitrogen has been exhausted a vector of 0 / 1 integer variables (ϑ) is defined:

$$\vartheta_{t,c} W \geq \eta_{t,c} \tag{5-7}$$

$$\varphi_{t,c} W \geq s\omega_{t,c} \tag{5-8}$$

$$1 \geq \vartheta_{t,c} + \varphi_{t,c} \tag{5-9}$$

where W is an arbitrarily large coefficient. When ϑ equals 1 permission is provided for nutrients to be transferred from the current to the subsequent period; and when φ is non-zero permission is provided for weed growth to occur at less than potential rates. Equation 5-10 ensures that either ϑ or φ must equal zero, so that soil nitrogen can only be transferred between periods if actual weed growth equals the potential rate of weed growth.

To formulate the MILP model of weed growth as a LP, the variables ϑ, φ_t and $s\omega$ are dropped from the model. It is not necessary, therefore, to include Equations 5-8 to 5-10. Actual weed growth is specified in the LP model as follows:

$$\Delta\omega_{t,c} = a6_t + a7_{t-1}\, \omega_{t-1,c} \tag{5-10}$$

The linear version of the weed growth model, adopts a slightly simpler but more restrictive assumption than the MILP model, in that actual weed growth is required to equal potential weed growth. In the LP model sufficient nitrogen must therefore be present so that weed growth is not constrained by nutrient availability. This contrasts with the MILP model which allows actual weed growth to be less than the potential rate of growth, and for soil nitrogen to limit crop and weed growth during periods when weeds are actively growing. This simplification may introduce distortion to the LP solution, as greater quantities of nitrogen may be applied, or more intensive weed control measures implemented than the MILP model would indicate as being optimal. However, it is not likely that this will introduce significant errors to the study. The equations presented above provide sufficient constraints to model the growth and inter-period transfers of weeds, and give a simple representation of reductions in crop yield that result from weeds competing with crops for soil nutrients.

The presence of weed material in the field reduces a combine harvesters ability to separate grain from crop and weed residues and increases requirements for crop drying (Cousens *et al*, 1985). Elliott (1980) suggests that threshing losses of grain become significant, if the rate of material other than grain (MOG) passing through a harvester exceeds a certain limit. For the purpose of this study, it is assumed that the quantity of straw material and weed dry matter, present at harvesting, are additive in terms of providing estimates of MOG and (as combine size is denoted in terms of capacity to process MOG per unit of time) the amount of time required to combine a field (M_l).

$$a9_1 \, M_{1,h,c} \geq S_c + \omega_{h,c} \qquad (5\text{-}11)$$

where, $a9_1$ represents the rate at which a combine harvester (kg DM. hour^{-1}) can process straw (S, kg DM), and weed material; and h is the month of harvest. Estimates of the parameter $a9_1$ can be found in Appendix 4.1; the quantity of straw that is produced is assumed to be a constant (see Table 5-3).

Table 5-3. Straw Yields (tonnes DM. hectare^{-1})

Crop	Straw
Spring Feed Barley	3.0
Winter Feed Barley	4.5
Winter Malting Barley	4.3
Winter Feed Barley	5.2
Winter Milling Wheat	4.8

Grain moisture levels at harvesting, and hence the requirement for drying (M_2, hours), are positively related to the presence of weeds (Davies and Whiting, 1990; Elliott, 1980; Sheppard *et al*, 1989; Zimdahl, 1980). The impact that weeds have on crop drying, is accounted for, in the model, by assuming a basal level of grain moisture that is incremented as a linear function of weed density. This is represented as follows:

$$M_{2,h,c} \geq a10 \sum_{t=1}^{12} \Gamma_{t,c} + a11\ \omega_{h,c} \qquad (5\text{-}12)$$

where, a10 and a11 are parameters that respectively represent the basal requirement to dry harvested grain, and the increment in drying that is associated with weeds. Parameter values necessary to represent the effects of weeds at harvesting are derived from a variety of sources including Elliott (1980); Sheppard *et al* (1989); and Whiting *pers. comm.*, (1995).

For crops that are grown to produce feed grains, the mechanism by which herbicides affect the model objective function, is by reducing weed levels and hence the influence that weeds exert on crop growth and harvesting; application of insecticides and fungicides are assumed to increase potential crop yield levels. The amount of fungicides and insecticides (P) that are applied to a crop is calculated as follows:

$$P_{t,c,i} \leq \min\ (a12_{t,c,i}\ a13_{t,c,i},\ a13_{t,c,i}\ a9_n\ M_{n,t,c}) \qquad (5\text{-}13)$$

where a12 is the number of spray applications that can be applied to a crop; a13 is the maximum amount of active ingredient that can be applied in a single application (kg hectare^{-1}); a9 is the work rate in hectare hour^{-1}; M is hours of work performed by a sprayer tractor combination; n identifies the actual machinery complement that performs the spray operation. The parameters a12 and a13 can be found in Table 5-2; and a9 is presented in Appendix 4.1.

5.2.4 Crop Nitrogen.

The cycling of nitrogen in soil involves complex and dynamic processes that have a considerable impact on farm practices and productivity (Pannell and Falconer, 1988). Also, the amount of nitrate pollution emanating from farms is of considerable public concern, and is affected by the interaction of the imposed management system and biologically determined transformations (Walther, 1988). In the context of this study a change in climate has significant implications for the cycling and losses of nitrogen between soil, plant and animal systems. The managerial activities that influence the availability of soil nutrients include, the crop rotation that is selected, the method and timing of cultivation, disposal method for crop residues, and the application of inorganic fertiliser and farm yard manure. An effort was made to represent the management options available to the farmer, and major nutrient flows, relevant to the single year time horizon of the model.

Variations in the amount of nitrogen present in the soil are explicitly modelled for the majority of crops and soil types. Flows of nutrients that occur between successive crops planted to the same ground, are tied to the rotational constraints included in the model. Farmers may physically augment the soil nutrient pool by applying inorganic fertilisers and farm yard manure, and by incorporating crop residues. In addition, leaching of nutrients from decaying vegetation, biological fixation of nitrogen, and reductions in the soil nutrient pool due to crop and weed uptake for growth, are represented in the model. Losses of nitrogen due to denitrification, volatilisation and leaching are modelled as functions of the soil type and time of year (Bloom *et al*, 1988; Chalmers and Darby, 1992; Chambers and Smith, 1992; Cole *et al*, 1987; Egginton and Smith, 1986a and 1986b; Gasser, 1979; Groot and Verberne, 1991; Powlson, 1988; Powlson *et al*, 1988; van Veen and Frissel, 1979; Whitmore and Parry, 1988); parameters associated with inter-period transfers of nitrogen provide estimates of losses from these sources.

The approach adopted to model the impact of nitrogen (η) availability on crop growth is similar to that first suggested by von Leibig (1855) who stated that a unit of a soil nutrient taken up by a plant, makes a constant contribution to growth so long as other nutrients are non-limiting. While providing a highly simplified representation of the effect of nutrients on crop growth, a number of experimental results have broadly confirmed von Leibig's model (Boyd *et al*, 1976; England, 1986). In the current model, the amount of mineral nitrogen present in the soil is represented as:

$$\eta_{t,c} = (1 - a14_{t-1})\,\eta_{t-1,c} + \omega\eta_{t,c} + c\eta_{t,c} + f_{t,c} + a15\,FYM_{t,c} + a16_{c}\,I_{t,c} \qquad (5\text{-}14)$$

$$\omega\eta_{t,c} = -\,a17_{t}\,\Delta\omega_{t,c} + a18\,(1 - a5_{t,c})\,\omega_{t-1} + a18 \sum_{m=1}^{n} c\omega_{t-1,c,m} \qquad (5\text{-}15)$$

$$c\eta_{t,c} = -\,a1_{c}\,\Gamma_{t,c} + a19_{c}\,(1 - a5_{t,c})\,\Gamma_{t-1,c} + \gamma\eta_{t,c} \qquad (5\text{-}16)$$

where a14 is the proportion of soil nitrogen that is lost from the preceding period due to leaching, denitrification and volatilisation; $\omega\eta$ is the effect of growing weeds on nitrogen (kg); $c\eta$ is the effect of the growing crop on soil nitrogen (kg); f is the quantity of fertiliser nitrogen applied to soil (kg); a15 is the available nitrogen content of farm yard manure (kg kg^{-1} FYM), and FYM is the amount of farm yard manure that is applied to the soil (kg); a16 is the quantity of nitrogen excreted by animals per kilogram of grazed pasture or crop residue; a17 is the amount of nitrogen taken up by growing weeds (kg kg^{-1} $\Delta\omega$); $\Delta\omega$ is weed growth (kg) (see Equation 5-11); a18 is the amount of nitrogen that is leached from dead weed material (kg kg^{-1} dead weeds); a19 is the amount of nitrogen that is leached from dead crop material (kg kg^{-1} crop material); $\gamma\eta$ refers to nitrogen that is derived from a range of sources (see Equation 5-17); a1 and Γ are defined in Equation 5-1; I and a5 are defined in Equation 5-3; $c\omega$ is defined in Equation 5-5 and $\gamma\eta$ is defined in Equation 5-17.

As arable crop growth is modelled in terms of increases in harvestable yield; increments in non-harvestable plant material are not explicitly considered. Cycling of nitrogen from dead plant material to the soil is therefore modelled as a function of nutrient uptake (see Figure 5-1). For determinate crops that pass through defined stages of development until the plant reaches maturity, this treatment is assumed to be adequate.

However, pasture exhibits an indeterminate growth habit and may be harvested in a variety of ways (such as being grazed in-situ, or conserved and removed from the field). In the case of pasture it is thought that a better approximation of nutrient flows can be achieved by assuming that matter returning to the soil as a result of maturation, death and decay, is a function of time of the year and the amount of pasture transferred between periods (see Figure 5-2); nitrogen that is excreted by grazing animals is assumed to contribute directly to soil nitrogen levels while conserved pasture is assumed to contribute to farm yard manure after it is fed to animals. A similar approach to that used to model flows of nutrients to the soil from processes associated with normal growth and death of pasture is used for weeds. Flows of nutrients that are contingent upon the decay of dead weed material resulting from chemical and cultural practices, are modelled as a function of the assumed efficacy of the applied control method.

In the current model it is assumed that nitrogen fixation, atmospheric deposition, nitrogen transferred from the preceding crop and the assumed level of mineralisation occurring in the different soils are additive in terms of the amount of plant available nitrogen present in a soil. The term used in this study to refer to these sources of nitrogen is $\gamma\eta$; $\gamma\eta$ is calculated for the different regions, soils and crop types and is dependent on the crop or crops that precede the current crop and on the method of residue disposal:

$$\gamma\eta_{t,c} = a20_{t,c} + a21_{t} + a22_{t} + a23_{t,c-1,d} + a24_{t,c-2} \qquad (5\text{-}17)$$

where a20 is the amount of nitrogen fixed by a crop; a21 is atmospheric deposition of nitrogen; a22 is the net amount of mineralisation; a23 is nitrogen that is transferred from the preceding crop; and a24 is nitrogen that is transferred from crops that are planted two years previously. The subscript d refers to the method of residue disposal; other subscripts have been defined previously.

Other assumptions that relate to the derivation of $\gamma\eta$ are that the amount of nitrogen fixed and the net amount of soil mineralisation occurring in different months of the year can be calculated from arrhenius equations, while the amount of atmospheric nitrogen deposition is assumed to be proportional to the rainfall occurring in the respective regions (Vinten *pers. comm.*, 1995). These assumptions represent a significant simplification of reality, particularly with regard to transformations that occur between mineral and organic forms of nitrogen (Campbell, 1978; Goss *et al*, 1991; Hauck, 1971; Jarvis, 1992; Powlson, 1992; Redman *et al*, 1988; van Veen and Frissel, 1979; Vinten and Smith, 1993). With regard to the current study, it was necessary to adopt these assumptions to ensure that issues associated with data acquisition were tractable.

The form of the arrhenius equation used to determine the net amount of soil mineralisation that occurs in each month, for the various regions, is as follows:

$$\frac{\Lambda\,(T_t)}{\Lambda\,(Ta)} = e^{(-9000\,(1/T_t\,-\,1/Ta))} \qquad (5\text{-}18)$$

where T is temperature (°Kelvin); Ta is the mean annual temperature of the region (° Kelvin); and Λ is the relative rate of soil mineralisation.

5.2.5 Crop Rotations.

The rotation that a farmer selects has important implications for crop yield, weed and disease control, machinery operations and nutrient cycling (Auld *et al*, 1987; Catt *et al*, 1992; Cousens, 1985; Doyle *et al*, 1984 and 1986; Lloyd, 1992; Rabbinge *et al*, 1989). In order to assess the implications of alternate crop rotations, it is necessary to have an understanding of the sequence that crops are planted in a field. Historically, the sequential nature of issues associated with rotations, and the potentially large number of rotations to be considered, has caused difficulties in studies involving linear modelling. This has meant that studies have generally been restricted to consider a few of the most likely rotations (Pannell and Panetta, 1986) or alternately to include very large numbers of activities that each represent a possible rotation (Hansen and Krause, 1989). Dent *et al* (1986) present an efficient method to constrain rotations; however, a difficulty with Dent *et al*'s approach, is that while information is supplied about the proportion of the farm that is planted to different crops, this data is not sufficient to uniquely identify (except when each crop can only be preceded by a single crop), the actual sequence that crops are planted to the same ground.

In this study a method has been developed which overcomes many of the shortcomings of previous approaches. The method is suitable for constraining crops, such as peas and potatoes that are widely grown and economically important crops, but which for pest control reasons, are only planted in the same ground once in a certain number of years. Crops that can only be followed by a restricted set of crops (such as oilseed rape following winter sown barley), because of the timing of field operations are readily accounted for. Also, factors that have implications for crops planted more than a year subsequent to a management action can be represented, an example in the current model is that nitrogen mineralisation rates are affected in the first two crops following pasture.

The methodology that is used to represent these rotations involves defining activities (nodes) to represent linkages between crops planted in succeeding years. Each rotational activity contains a pair of unitary coefficients, which specify the crops that precede and follow the current crop. When the model is solved, the nodes chain together to form rotations, that can represent any number of years, and give a generally optimal solution. The rotational nodes are defined in terms of (1) the crop that is to be planted; (2) the number of years since a crop constrained because of pest control requirements is planted; and (3) the preceding crop or crops if a crop planted more than a year previously has implications for the current crop.

An example sub-matrix is included in Figure 5-5 to demonstrate the method. In the example, three possible crops, X, Y and Z, are constrained by a requirement for land. Crops X and Y can be grown in any sequence, but crop Z can only be planted after crop Y. A further restriction is that crop X can only be planted once every 3 years. The naming conventions used in Figure 5-5 are: for the first 3 activities, the letter refers to the crop that is being planted; for the remaining activities, the first letter refers to the crop being planted, the second character refers to the number of years since crop X is planted, and the third letter refers to the preceding crop. For the first three constraints, the naming conventions are the same as for the first three activities; the fourth constraint refers to the requirement for land; and for the remaining constraints the first and second characters are defined in the same manner as the second and third characters of the rotational activity names.

The first three activities in Figure 5-5 refer to the crops X, Y and Z, and the first three constraints represent permission to plant these crops. The fourth and fifth activities refer to rotational activities that provide permission for crop X to be planted following crops Y and Z respectively. For both of these activities, crop X has not been planted for at least 3 years prior to these crops. The sixth activity in the matrix refers to crop Y being planted, a year after crop X. Due to the requirement that crop Z can only follow crop Y, there is no activity that would allow crop Z to be planted a year after crop X and for the same reason it is not possible for a crop to be planted 2 years after X and one year after Z. The seventh and eighth activities refer to crop Y following an earlier crop of Y. In the case of the rotational activity Y3Y, this activity represents a crop that is in a steady state, so that the only rotational constraint that needs to be specified is the requirement for land. The ninth activity is for crop Y to follow crop Z, it can be seen that this activity can only enter the farm plan if the tenth or eleventh activities in the matrix, which represent crop Z, also enter the farm plan.

Figure 5-5. Example Sub-matrix of Rotational Constraints and Activities.

			Cropping Activities			Rotational Activities							
			1	2	3	4	5	6	7	8	9	10	11
			X	Y	Z	X3Y	X3Z	Y1X	Y2Y	Y3Y	Y3Z	Z2Y	Z3Y
X	0	≥	1			-1	-1						
Y	0	≥		1				-1	-1	-1	-1		
Z	0	≥			1							-1	-1
LAND	A	≥				1	1	1	1	1	1	1	1
1X	0	=				-1	-1	1					
2Y	0	=						-1	1			1	
3Y	0	=				1			-1		-1		1
3Z	0	=					1				1	-1	-1

The method used to model alternate sequences of crops is very flexible and capable of addressing realistic problems at acceptable cost in terms of the number of required activities. In the above example, 8 activities are needed to specify all possible rotations for any length of time horizon. This compares to 16 activities, if each of the feasible rotations in the example occurring over a six year time horizon is explicitly represented. If a longer time horizon is considered the number of activities that must be specified increases rapidly. Although the presented methodology provides an efficient method of modelling crop rotations, the number of crops that are included, and the restrictions associated with the entry of crops still mean that rotational activities represent a significant proportion of the activities included in the model[75].

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[75] There are approximately 25000 activities involved in modelling crop rotations or 10 % of the total model.

The above representation is a simplification of the actual model, but is presented to illustrate the linking of differing crop sequences together. In the actual model, rotational activities require appropriate actions to be taken to dispose of crop residues, rather than (as illustrated in Figure 5-5) to directly provide permission to plant a crop. In turn the activities that represent residue disposal provide permission for an incoming crop to be planted. The method of modelling crop residue disposals is discussed below.

5.2.6 Crop Residue Disposal.

Activities relating to crop residue disposal are tied to the rotational activities, so that requirements for labour and machinery, and also the implications of the method of disposal for transfers of nitrogen to the subsequent crop, are modelled appropriately. As mentioned above, rotational activities specify the requirement for residue disposal and the disposal activity permits an incoming crop to be planted. The presented methodology provides a mechanism that allows crops to be planted during different months, and for the model to select the method of crop residue disposal.

For the majority of crop sequences, residue disposal grants permission for an incoming crop to be sown on any of the designated planting periods. For other crop sequences, the harvest and residue disposal of a crop can interfere with the planting of a following crop. When this occurs, the rotational activities provide permission for residue disposal to occur after the harvest of the outgoing crop; and the earliest that an incoming crop may be planted is the second or third of the defined sowing dates[76].

It is assumed that baling and grazing of crop residues occurs in the month of harvest. Grazing and baling of crop residues are assumed, therefore, not to affect the date that a following crop is planted. Activities that represent incorporation of field residues are tied to the following cropping activity, so that the timing of incorporation is the same as the cultivation date of the incoming crop. The method of relating rotational activities to residue disposal activities, and in turn, for disposal activities to be linked to the planting dates of an in coming crop is illustrated in Figure 5-6.

In Figure 5-6, the residue disposal options, and alternate planting dates of a crop are illustrated for a situation where the planting date of an incoming crop is not

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[76] Please note that only a single planting date is represented for swedes, see Table 5-1.

restricted and all of the modelled disposal methods (incorporation, baling and grazing) are available to the farmer. The first column in Figure 5-6 is a rotational activity that defines the requirement for residue disposal. Nitrogen that is derived from a crop planted two years previously is specified in this column (see a24 in Equation 5-17). The second column relates to a crop that can be planted on three different dates. The implications of the crop for the soil nitrogen status (see a20, a21 and a22 in Equation 5-17) are specified for each of these planting dates.

The third, fourth and fifth columns represent alternative methods of residue disposal. The disposal activities are defined for each soil and feasible crop sequence. If incorporation is selected, a crop is permitted to be planted, and the influence of ploughing in residues on the soil nitrogen status of the incoming crop (see a23 in Equation 5-17) is defined. In the case of baling, crop planting is permitted, and the requirements for machinery and labour to perform windrowing and baling operations are specified. The action of baling supplies straw for subsequent use as feed or bedding. The final method of residue disposal involves grazing of crop residues. In the same way as incorporation and baling, grazing provides permission for a crop to be planted and crop residues are made available to grazing animals. It is assumed that nitrogen contained in the excretion of grazing animals is transferred to the soil on which the incoming crop is to be planted (see a16 in Equation 5-14).

As mentioned above, the method of disposing of a crops residue may be restricted for management reasons (such as the requirement that undersown feed barley residues are baled as straw), and also the earliest that a crop can be planted may depend on the harvest date of the preceding crop. In these cases, only variables that represent acceptable timings and methods of disposal are included in the model. Parameter estimates associated with the influence of alternate sequences of crops, and methods of residue disposal on soil nitrogen are discussed in Section 5.3.6.3.

Figure 5-6. Residue Disposal and Planting of Crops[77].

			Rotational activities	Crop activities			Disposal Method								
							Incorporation			Bale			Graze		
Requirement for Residue Disposal	0	=	-1 [78]				1	1	1 [78]	1	1	1 [78]	1	1	1 [78]
Permit Crop	0	≥		1		[79]	-1		[79]	-1		[79]	-1		[79]
	0	≥			1			-1			-1			-1	
Planting	0	≥				1			-1			-1			-1
Straw in field	0	≥											-A	-A	-A [80]
Baled straw	0	≥								-A	-A	-A [81]			
	0	=	-A [82]	-A	-A	-A [83]	-A		[84]	-A		[84]	-A		[84]
Soil Nitrogen	0	=		-A	-A	-A		-A			-A			-A	
	0	=		-A	-A	-A			-A			-A			-A

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[77] 'A' refers to non-zero coefficients that are not equal to unity.

[78] Each of the rotational activities specify a requirement for residue disposal which can be in the form of incorporation, baling or grazing.

[79] The timing of residue disposal depends on the planting date of the incoming crop.

[80] Grazing of crop residues supplies metabolisable energy and indigestible dry matter to livestock.

[81] Baling of crop residues supplies straw which can subsequently be used for feed or bedding or be sold.

[82] Transfer of nitrogen from crops planted two years previously (see a24 in Equation 5-17).

[83] Soil nitrogen that is derived from fixation, atmospheric deposition and mineralisation (see $\gamma\eta$, in Equation 5-17).

[84] Soil nitrogen that is transferred from the previous crop is a function of the outgoing crop and the method of residue disposal (see a23 in Equation 5-17).

5.3 Estimation of Model Parameters.

Many of the parameters included in the LP crop models are derived from simulation models that are sensitive to the selected climate, soil, and management variables. However, in the case of swedes and weeds, no suitable models were found in the literature. Due to the highly seasonal nature of forage production in Scotland, swedes can be essential for the success of sheep farming systems. If swedes are not represented in the LP model due to the inability to obtain an acceptable simulation model, the results of the study are likely to be biased against sheep operations. The importance of sheep to Scottish agriculture means that it is desirable to include, at least, an example of a forage crop in the LP model.

With regard to weeds, as mentioned previously, a critical effect of climate change is likely to involve changes in the incidence of weeds. The inclusion of weeds is therefore of value if the objectives of this study are to be satisfactorily addressed. The absence of acceptable simulation models for swedes and weeds means, however, that changes in the growth of these plants, can not be predicted with any degree of assurance for different climates, regions or soils. In the current study, estimates of swede and weed growth are derived from the literature and from experimental data (see Section 5.3).

A shortcoming that is common to all of the simulation models that were selected to represent crop growth is that the fertilisation effect of elevated carbon dioxide levels is not considered. A number of studies have indicated that crop yields are likely to be affected by increases in atmospheric carbon dioxide that are consistent with the climatic changes considered here (Jones *et al*, 1993; Ryle and Powell, 1992). With the exception of the grass and grass / clover models of Topp and Doyle (1994), the simulation models that provide inputs to the current study were not specifically developed to evaluate the influence of climatic change. With regard to the Topp and Doyle models, the effect of carbon dioxide on forage production is not represented, due to difficulties of obtaining suitable data (Topp *pers. comm.*, 1995). Ideally, the estimates of crop growth and yield that are used in this study would incorporate the influence of carbon dioxide particularly as elevated carbon dioxide levels are likely to have a differential impact on crops and weeds that employ a C3 versus a C4 photosynthetic pathway (Edwards and Walker, 1983). However, it was beyond the scope of this study to explicitly evaluate relationships between carbon dioxide and plant growth.

5.3.1 Grass and Grass / Clover Models.

Parameter estimates for grass and grass / clover swards are established using time series data produced by the models of Topp and Doyle (1994). Topp and Doyle's models were developed and tested in a project analysing the effects of climate change in Scotland and as such represent a high quality source of data. The pasture models of Topp and Doyle were used to evaluate a range of grazing and conservation management practices across a number of years, soils, regions, animal types, stocking rates and climatic change scenarios. The models assume that pasture is comprised either of grass or a mixture of grass and clover. The growth of pasture is modelled on a daily basis on each of a user specified number of fields. It is assumed that production is dependent on herbage mass, temperature, radiation, and the availability of nutrients and water. In the model, leaf, stem, root and dead material are separately represented for both the grass and clover components.

The data produced by the Topp and Doyle models, are used to estimate relatively simple models of grass and of grass / clover that are specific to the soils, regions and climates that are considered in this study. The scenarios and management variables used to estimate the pasture models are identical to those used to establish the animal growth models presented in Chapter 6. The scenarios that are evaluated include three animal systems (dairy, beef cattle, and sheep), three stocking rates (low, medium and high), two pasture classes (grass and grass / clover), three climate change scenarios (climates ‘0’, ‘1’ and ‘2’), four regions (Kinloss, Mylnefield, Paisley and Wick) over a ten year period and for four soil types.

The method of forage conservation considered by Topp and Doyle is silage making (Topp *pers. comm.*, 1995). In the LP model, hay making is also considered. Silage tends to be conserved earlier in the season than hay, and has differing requirements regarding the moisture content of the sward and weather conditions at the time of harvest. However, in the context of this study time constraints prevented the inclusion of a rule base in Topp and Doyle's model that would better represent decisions relating to the timing of hay making. In the LP model, cutting of hay and silage are assumed to occur on the same date.

As mentioned in Section 5.2.2, in the LP model both grass and grass / clover are categorised in terms of the method of forage conservation that is employed. These categories are pasture that is cut for hay, pasture that is cut for silage and pasture that is only available for grazing. The method of classifying pasture in terms of whether the pasture is comprised of grass or grass / clover, and also in terms of the method of forage conservation that can be implemented, produces a total of six possible classes of pasture. In addition, pasture classes are defined for each soil, so that a total of 24 pasture classes are included on farm types where pasture is represented. For each of these classes, the amount of pasture in the sward is reconciled on a monthly basis in terms of the amount of growth, senescence, and animal intake. The requirements for machinery to perform conservation operations are also specified for each of these classes.

The estimates of potential growth (a2 in Equation 5-3) are established by averaging leaf growth during each month (averaged in terms of leaf dry matter production per hectare across the fields included in the Topp and Doyle models), that occurred for the various animal systems, years and stocking rates considered. The calculation of the inter-period losses in leaf material (a5 in Equation 5-3) involved determining the difference between the amount of leaf material present in the sward at the beginning and end of each month and comparing this figure with the amount of growth, less the sum of material ingested by ruminants and mechanically harvested. The difference in these values is attributed to death of leaf material. The parameter a5 is calculated as the ratio of leaf that dies to the average amount of leaf material present in the sward.

The estimates relating to pasture growth are specific to each pasture type (that is grass or grass / clover), region, climate, and soil. Parameters relating to pasture losses are calculated for both grass and grass / clover, but following Topp and Doyle (1994), the proportion of leaf that dies is assumed to be the same for the different regions, climates and soils. In the case of grass / clover swards, sward growth and losses are calculated as the summation of grass and clover. The parameters are assumed to be identical for the different methods of forage conservation and animal types and are an average of the ten seasons of simulated growth.

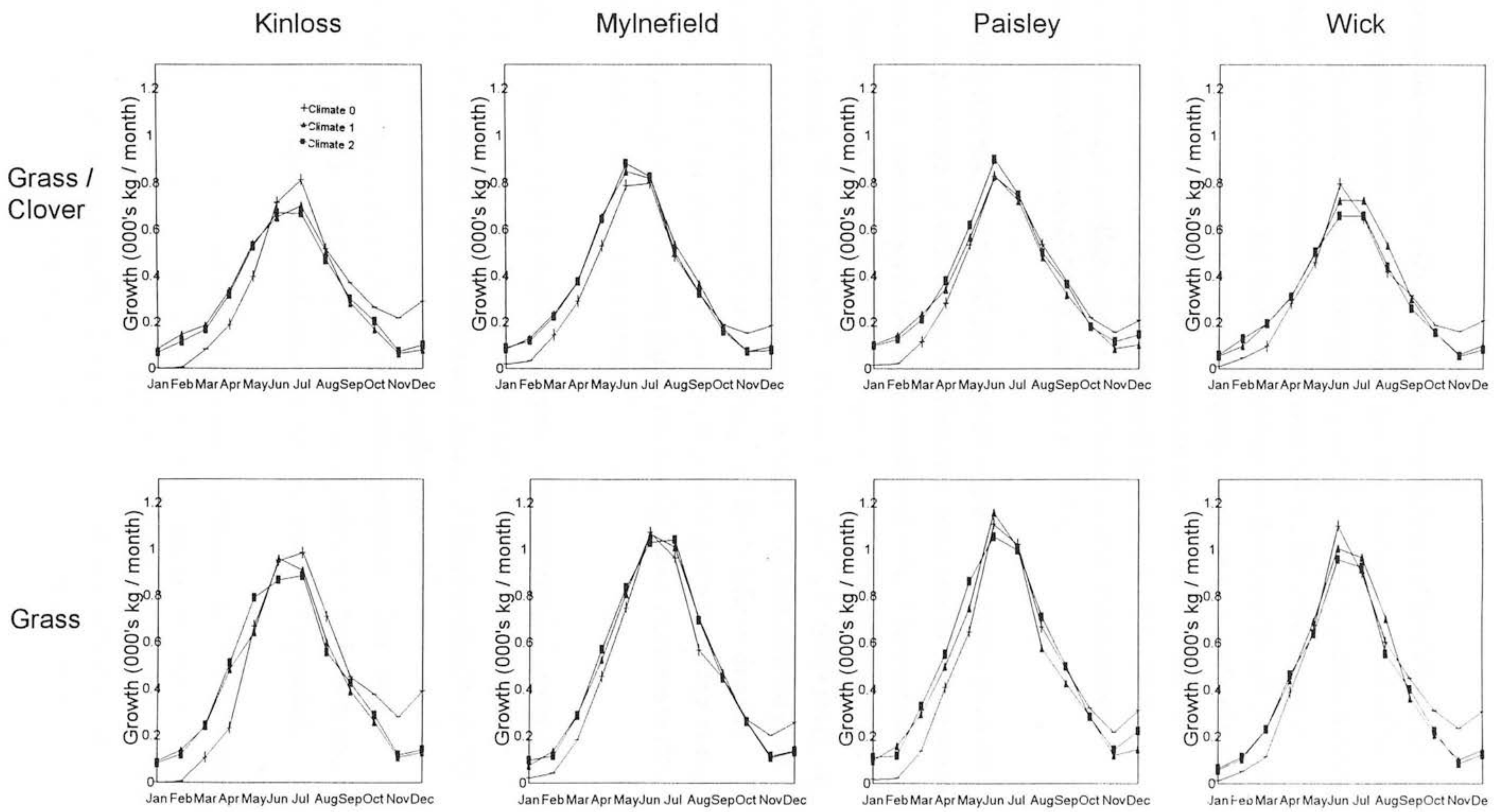
In the LP model, stocking rate is an endogenous variable, rather than an exogenously determined variable as in Topp and Doyle's model. An implication of the selected formulation is that although stocking rate and grazing management can influence the amount of pasture that accumulates in a sward, it is assumed that the stocking rate does not affect the potential rate of pasture growth, the period that animals are grazed in the field or the timing of forage conservation.

A summary of the estimates of potential growth of grass / clover and grass (a2 in Equation 5-3) for soil 4 is presented in Figure 5-7. A complete listing of the potential growth estimates can be found in Appendix 7. The significance of the effect of climate change is assessed at each site using an analysis of variance test on differences in mean annual production between the selected climatic scenarios (Genstat, 1994) (see Appendix 6). In the following discussion the scenarios referred to in this study as the current climate (climate '0') and a climate involving an increase in temperature and associated change in rainfall (climate '1') (see Section 2.1) are the same as scenarios '1' and '4' from Chapter 5 of Topp and Doyle. It should be noted that Topp and Doyle did not consider a scenario that was equivalent to climate '2'.

The parameters estimated from Topp and Doyle's (1994) scenarios showed little difference between the various soil types. On an annual basis the differences in potential production are generally less than 5 percent between the least and most productive of the soil types. Although there is a trend for the heavier soils to outyield the lighter soils, these differences are not significant. From Figure 5-7, the estimates of potential production suggest that relatively small differences in productivity exist between the different regions. In general Paisley is the most productive of the regions and Wick is the least productive. Kinloss and Mylnefield tended to be intermediate between these regions. Also as reported by Topp and Doyle (1994), the impact of climatic change on forage yields produced inconsistent results.

From Figure 5-7, it can be seen that potential pasture production exhibits a marked seasonal pattern with a single peak in production occurring in June or July. Under current climatic conditions winter production (December - February) for both grass and grass / clover is approximately 10 percent of the annual total, compared with approximately 50 percent in summer (June - August). In spring, production tends to be slightly higher than in autumn. Approximately 22 percent of grass and grass / clover production occurs in spring compared with 18 percent in autumn.

Figure 5-7. Potential Growth of Pasture (see a2 in Equation 5-3)



When comparing climate '0' with climate '1', the seasonality of production for both grass and grass / clover declines by a small amount. Increases in production occur in spring, however, the relative increase in production at the beginning of the season is largely offset by reductions in autumn production. The proportions of production occurring in winter and summer are similar for the three climatic scenarios considered. It is uncertain why levels of productivity in autumn have declined under the changed climates, as the warming associated with these scenarios might be expected to increase production during this period (Flohn, 1985). A possible explanation is that changes in other weather factors such as solar radiation and rainfall, have produced this result (Topp *pers. comm.*, 1995).

At Wick, small increases in potential productivity of grass / clover and grass are estimated between climate '0' and climate '1'. However, the extent of yield increase is not significant on an annual basis for all of the considered soils. This compares with a non-significant reduction of approximately 5 percent in potential production that occurs between climate '0' and climate '2'. This outcome differs from the results of Topp and Doyle who found a significant increase in pasture production from grass swards, when comparing climates '0' and '1' (Topp and Doyle refer to these as scenarios '1' and '4'). For grass / clover swards, Topp and Doyle found that changes in the amount of grass harvested are not significant, but significant increases in clover production in grass / clover swards occurred.

At Paisley, estimates of potential grass and grass / clover production increase by approximately 5 percent between the base climate and climate '1'. Similarly, the annual increase between the current climate and climate '2' is approximately 8 - 10 percent. Neither of these comparisons represent a significant change in annual production for any of the soils at a level of 5 percent significance. This result concords with Topp and Doyle (1994) who found no significant differences at this site, for either grass or grass / clover production, with increases in temperature.

At Kinloss there is no significant change between the climatic scenarios for either grass or grass / clover in terms of the estimates of potential pasture production. This result is similar to the outcome of Topp and Doyle's (1994) analysis, which found no significant differences for grass swards. For grass / clover swards, declines in the production of grass with increasing temperature, tended to be cancelled by increases in clover. The overall productivity of grass / clover swards is therefore relatively similar for the different climate scenarios.

At Mylnefield an increase in the potential productivity of swards of approximately 10 percent is recorded when comparing climate '0' with climate '1'. The difference between these climatic scenarios is significant for three of the four soils. Topp and Doyle (1994) report an increase in yield for the grass swards of approximately 10 percent between scenarios '1' and '4'. For these same scenarios, Topp and Doyle also found an increase in total yield of grass / clover swards of a similar order to the current study. The increase in potential production between climates '0' and '2' is approximately 5 percent, and is non-significant, for both the grass and grass / clover swards.

Although the results for Kinloss, Mylnefield and Paisley provide similar rankings and magnitudes of response to Topp and Doyle's (1994) experiments, differences exist with respect to estimates for Wick. The current study is not strictly comparable to the results of Topp and Doyle, and is presented for illustrative purposes. The experiments performed by Topp and Doyle utilise different weather series and also a number of the assumptions, particularly those relating to the soil characteristics and grazing management are different to those adopted in this study. Also, the analysis performed by Topp and Doyle records changes in the yield of conserved forage, while the estimates discussed here refer to annual changes in potential yield.

The proportion of leaf losses associated with death and decay in each period are presented in Table 5-4. The monthly losses range from a low in winter of approximately 0.55 to a maximum in summer of 0.87. When evaluating the time series data produced by the Topp and Doyle (1994) models, there appeared to be little difference between the scenarios that are considered. The results are relatively consistent between the different climates, regions, years, animal systems, and stocking rates. There are small non-significant differences between grass / clover and grass pastures, with slightly lower losses occurring on grass / clover pastures. In Topp and Doyle's model, the proportion of leaf material that senesces is higher for grass than clover. As clover represents a relatively small proportion of a growing sward, these results appear to be consistent with Topp and Doyle's findings.

There is evidence to suggest that sheep graze more selectively than cattle (Nicol, 1987) and that the ability of animal to selectively graze increases with pasture cover

(Clark *et al*, 1982). It has also been suggested that clover is ingested by animals in preference to grass, due in part to the greater palatability of clover and also because of differences in the vertical distribution of clover and grass within a sward (Woledge *et al*, 1992). However, when Topp and Doyle's time series data were aggregated into a form suitable for this study, an analysis of variance showed no significant differences between regions, climates, soils, years, stocking rates, or animal types in terms of metabolisability or digestibility of pasture or sward composition. Whether differences of these types are present in the original data series of Topp and Doyle is not known, but given the results of the analysis it seemed appropriate to estimate the metabolisability and digestibility of pasture for each month as an average of the different regions, climates, soils, years, stocking rates, and animal types (see Table 5-4). Parameters that relate to the metabolisable energy content and digestibility of other feedstuffs that are included in the LP model can be found in Table 6-1.

Table 5-4. Grass and Grass / Clover Parameters.

Month	Proportion of Leaf Losses Occurring in each Period (fraction, see a5 in Equation 5-3)		Metabolisable energy ingested per kg of leaf (MJME.kg DM^{-1}, see a27 in Equation 6-7)		Indigestible material ingested per kg of leaf (kg kg^{-1}, see a29 in Equation 6-8)	
	Grass / Clover	Grass[85]	Grass / Clover	Grass	Grass / Clover	Grass
January	0.55	0.63	15.24	14.68	0.94	0.97
February	0.57	0.59	15.21	14.68	0.94	0.97
March	0.68	0.69	15.24	14.68	0.97	0.99
April	0.56	0.63	15.93	15.41	0.99	1.03
May	0.65	0.70	16.45	15.37	0.99	1.01
June	0.69	0.69	15.76	15.18	0.97	1.01
July	0.87	0.83	15.87	15.30	0.98	1.02
August	0.68	0.80	16.27	15.38	0.99	1.01
September	0.74	0.75	15.74	15.23	0.98	1.02
October	0.68	0.70	15.66	15.20	0.98	1.01
November	0.65	0.70	16.28	15.23	0.99	1.02
December	0.64	0.67	16.17	15.22	0.98	1.02

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[85] It is assumed that the proportion of leaf losses associated with weeds is the same as for grass.

5.3.2 Potato Model.

The parameters relating to the potential growth of potatoes are estimated using time series data from a simulation model presented in Jefferies and Heilbronn (1991). This model was first developed by MacKerron and Waister (1985), and MacKerron (1985), and subsequently extended in Jefferies and Heilbronn (1991) and Jefferies *et al* (1991) to incorporate the influence of water stress on potato growth. Although this model does not explicitly address issues of soil fertility, this is unlikely to reduce the models utility with regard to the current study, as farmers tend to plant potatoes on their most productive land, and fertilise the crop so that soil nutrients are non-limiting (MacKerron *pers. comm.,* 1996). For this reason, the effect of nitrogen on potato growth is not explicitly modelled in the LP study. The extensive testing and use of the potato simulation model at a number of locations in Britain means that it is well suited to be used in this study.

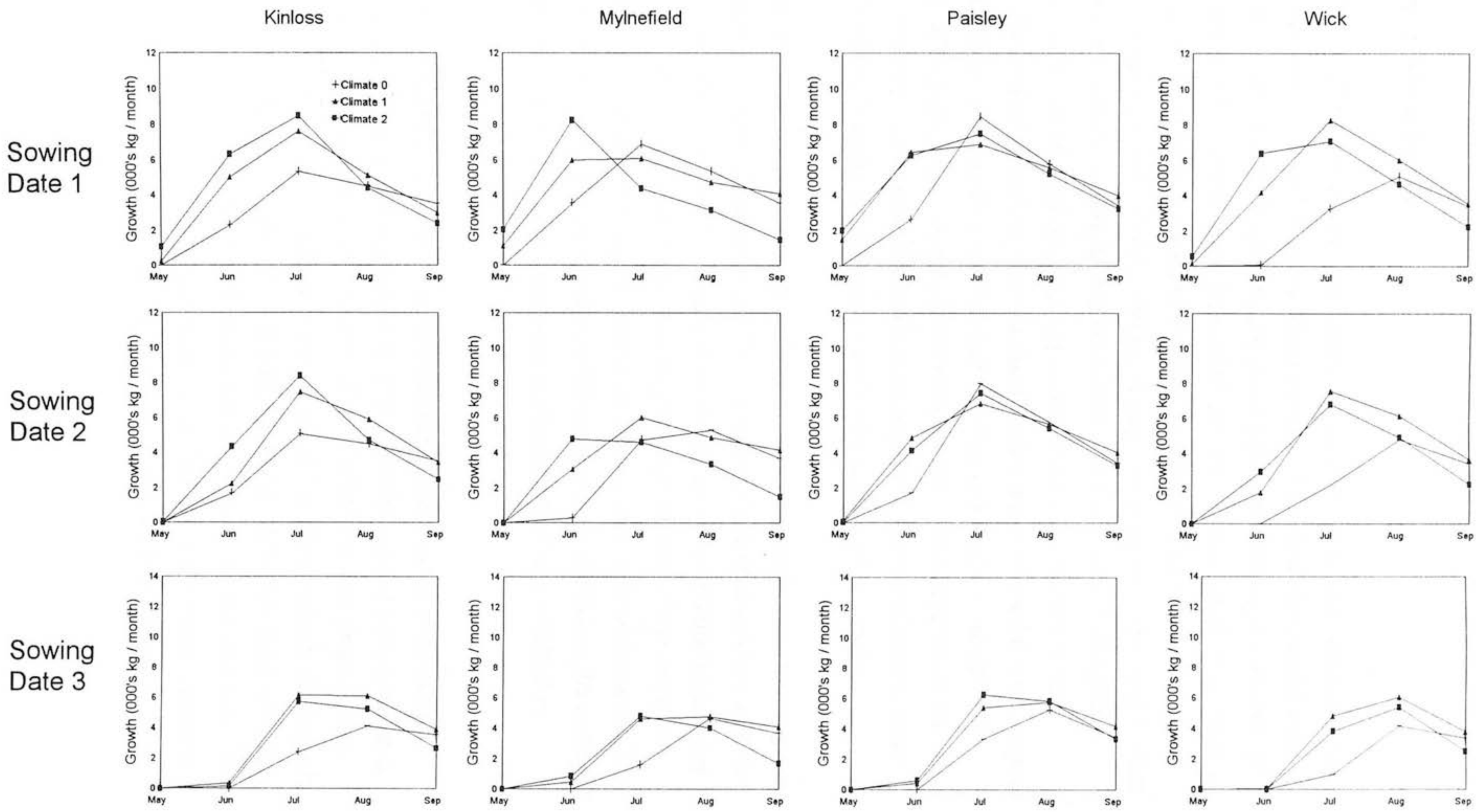
The scenarios considered for potatoes are three possible climates, four regions, two soil types, and three planting dates. The potential growth of potatoes is calculated by averaging the results achieved by running the simulation model with ten years of weather data. As mentioned in Section 5.2.1, potatoes are only permitted to be planted on the two most productive soil types considered in the model (see Table 5-1). The dates of planting and harvesting and other field operations are presented in Appendix 5. In the potato model, the effects of soil nitrogen and weeds, and also the effects of pesticide application on crop growth, are not considered. As the estimates of potential growth are not constrained by these factors, actual crop growth is assumed to be a direct function of the weather that occurs during the time that the crop is in the ground.

Estimates of the mean annual potential production of potatoes are presented in Appendix 6. Under current climatic conditions, Paisley is the most productive of the regions. Mylnefield, Kinloss and Wick follow in descending order of productivity. A comparison of climate '0' and climate '1' shows a significant increase in potential crop yield for the various regions and also a change in the relative productivity's of the regions. At Mylnefield the increase in potential yield with a change in climatic conditions is less than for other regions. As for climate '0', Paisley is the most productive region, and is followed in declining order by Kinloss, Wick and Mylnefield. With respect to climate '2', there is an increase in the estimates of potential yield when compared with climate ‘0’, but the increase is less than for climate ‘1’. The relative ranking in the productivity of the different regions is the same for climate ‘1’ and climate ‘2’.

The estimates of monthly changes in the potential productivity of potatoes are presented in Figure 5-8 for the various regions and sowing dates considered. The date of sowing has a large effect on estimates of potential yield, with earlier sowing producing higher potential yields than later planting dates. The potential productivity of potatoes that are planted on the earliest sowing date (sowing date ‘1’) are 15 percent higher on average than those planted on sowing date ‘2’. A similar comparison between the first and last sowing dates shows a difference of approximately 35 percent.

For sowing date ‘1’, with the exception of Wick, where the maximum rate of growth for climate ‘0’ occurs in August, the maximum potential growth rate occurs in June or July. If the time of planting is delayed until sowing date ‘2’ or ‘3’, the period of maximum growth is generally later by one or two months but there do not appear to be compensatory increases in growth during the later months of growth. With a change in climate, growth rates tend to increase during the first two or three months that the crop is in the ground. In later months there is little difference between the climatic scenarios in terms of rates of potential growth.

Figure 5-8. Potential Growth of Potatoes (see a2 in Equation 5-2)



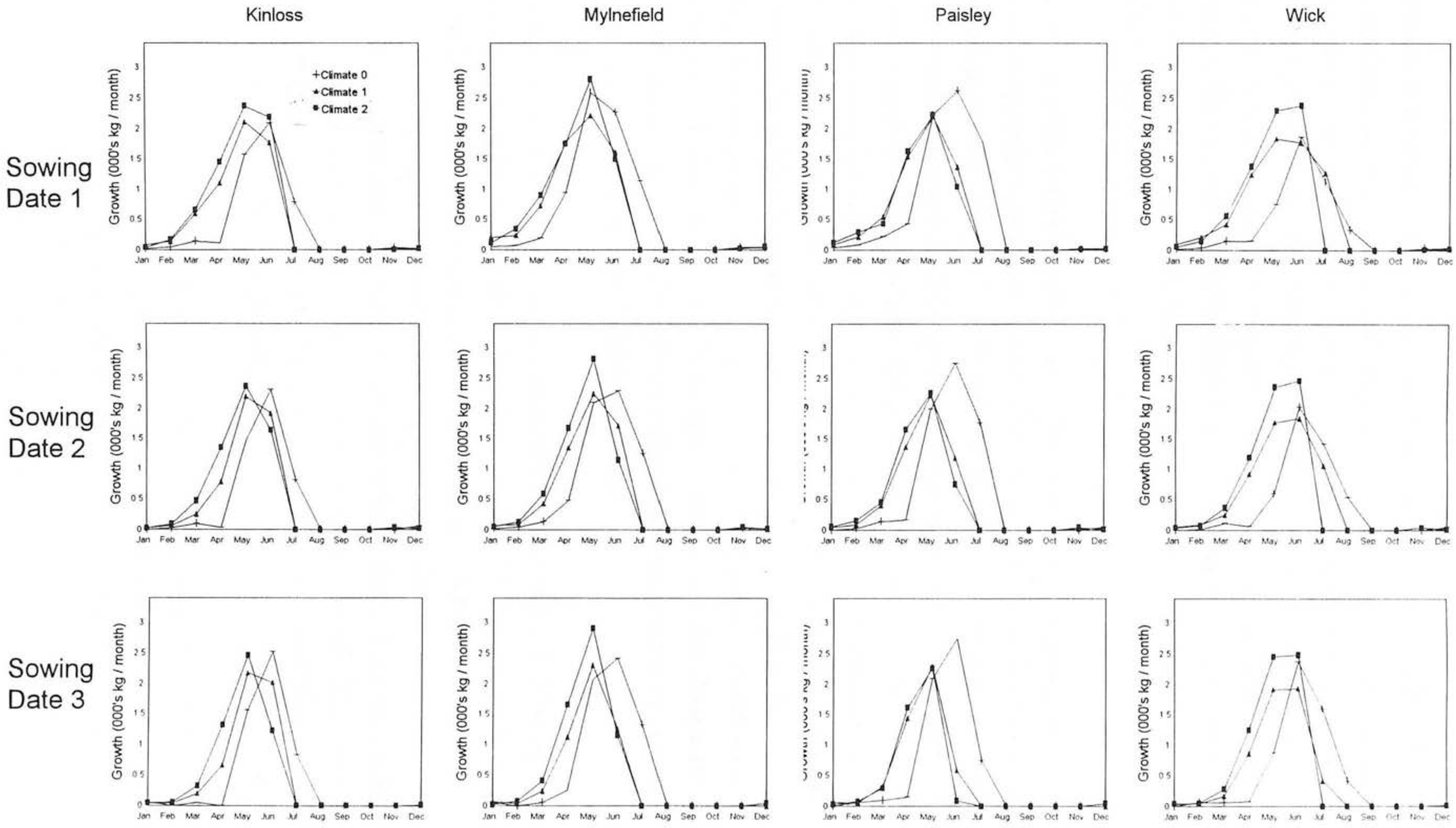
5.3.3 Winter Wheat Model.

The AFRCWHEAT2 model (Porter, 1993) is used to provide time series data for estimating parameters in the LP winter wheat models. This simulation model was initially developed to model the growth and development of wheat in the absence of water and nitrogen limitations (see Porter, 1983 and 1984; Porter *et al*, 1982; Weir *et al*, 1984a) and subsequently updated to incorporate a detailed representation of soil water and nitrogen dynamics (Porter, 1993). A major assumption of the model is that temperature and light determine the maximum rate of crop growth. Sub-optimal amounts of water and nitrogen are assumed to reduce actual yields below this potential. The revised model has been validated against data collected from a range of British sites, years, sowing dates and fertiliser regimes, and produces acceptable predictions of crop development and yield (Porter, 1993). The validation of the model, and the inclusion of yield responses to nitrogen and water availability, make the AFRCWHEAT2 model an appropriate tool in the context of this study.

The scenarios that are considered for winter wheat are three climates, four regions, four soil types, and three planting dates. The estimates of potential yield are specific to each of these scenarios and are calculated as an average of ten simulated growing seasons. It is assumed that feed wheat may be planted on all four of the modelled soils, while milling wheat may only be planted on the two most productive soils. The estimates of potential growth are established for each scenario relative to the timing of field operations and the rates of soil nitrogen applications that are presented in Appendix 5.

The AFRCWHEAT2 model does not account for differences between cultivars when estimating crop yield. It is assumed that the potential yield of milling wheat is 95 percent of the estimates derived from the AFRCWHEAT2 model (Russell *pers. comm.*, 1995). In the case of feed wheat it is assumed that the maximum yield equals the estimates established from the AFRCWHEAT2 model. A further point relates to the assumption in the AFRCWHEAT2 model that crops are weed and pest free. The estimates of the potential yield of feed wheat (see a2 in Equation 5-2) are adjusted to reflect the assumed contribution to potential yield of pesticide applications.

Figure 5-9. Potential Growth of Feed Wheat (see a2 in Equation 5-2)



As little data is available to evaluate the impact of pests or the likely effect of pesticide applications on the yield of feed wheat it is assumed that the yield increment associated with pesticide applications equals 10 percent (Davies et al, 1989) of the potential yield estimated from the AFRCWHEAT2 model. Also, the presence of weeds in a winter feed wheat crop is assumed to reduce potential crop yield below the estimates established from the AFRCWHEAT2 model. The extent of yield reductions associated with weeds is established from experimental data presented in SAC Annual Bulletins (see Appendix 8).

The estimates of the potential yield of winter feed wheat are summarised on an annual basis in Appendix 6 and monthly parameters for the heaviest soil type (soil '4') are presented graphically in Figure 5-9. Parameters relating to winter milling wheat are also presented in Appendix 6. With respect to the influence of soil type, there appears to be a relatively consistent relationship between the different soils with respect to differences in the potential productivity of feed wheat. On average, the lightest soil (soil '1') yields approximately 15 percent less than the heaviest soil (soil '4'). The potential yield of feed wheat planted on soils '2' or '3' tends to be intermediate between crops grown on soils '1' and '4'. The pattern of variations in the potential yield of wheat that occur with changes in sowing date and climate are more complex than for potatoes. The following discussion relates to the influence of sowing date and climate for both feed and milling wheat.

Given the current climate, delaying the sowing date has the effect of reducing potential crop yield at Paisley and Mylnefield. Conversely at Kinloss and Wick, a delay in the date of sowing results in a small increase in yield. A possible reason for this is that at Kinloss and Wick low temperatures early in the growing period may limit crop yield. Paisley and Mylnefield are warmer on average than Kinloss and Wick so that crops are less likely to be exposed to low temperatures after planting. With an increase in temperature consistent with climates '1' and '2', all of the regions produced higher yields with earlier planting dates.

For the current climate, Paisley is the most productive of the regions and is followed by Mylnefield, Wick and Kinloss. However, the regional ranking of productivity is likely to change if the weather conditions associated with climates '1' and '2' eventuate. The estimates of crop yield at Wick increase with a change in climate, while at Paisley, there is a reduction in estimated yields with a similar change in climate. At Kinloss there is a significant increase in yield with a change in climate, but the extent of this increase is less than occurs at Wick. At Mylnefield, there is a non-significant reduction in yield associated with a change in weather conditions to climate '1' or '2'. There is little difference between the estimated rankings of the regions for either climates '1' or '2'. For these climates, Wick and Mylnefield are likely to have similar productivity levels and they are followed by Kinloss and Paisley.

5.3.4 Swedes.

As a suitable simulation model of swedes was not available, the potential yield of swedes is estimated from the literature. From SAC (1994) it is assumed that the yield of swedes is 8,000 kg dry matter per hectare on each of the soil types and regions that are represented. All of the dry matter produced, by swedes is assumed to be available to grazing sheep. Because of the poor quality of available data, the structure of the swede model is simpler than for other crops that are included in the LP model. No account is taken of weed growth or nitrogen uptake and only a single sowing date in May is considered. It is assumed that pesticides, fertiliser, and farm yard manure are applied to the crop at the rates specified in Appendix 5.

5.3.5 Other Crops.

Parameters for the remaining arable crops are estimated from time series established using a generalised model of crop growth and yield presented by Kvifte (1987). These crops include vining peas, winter oilseed rape, spring feed barley, spring feed barley that is undersown with pasture, winter feed barley and winter malting barley. The model runs that are performed with Kvifte's model include three sowing dates, a single soil type (soil '4'), four regions, three climate scenarios and ten years of weather. Kvifte's model is responsive to solar radiation, and incorporates the effect of water stress on crop yield. The simulation model was developed for Scandinavian conditions and adopts much simpler assumptions with regard to the growth and development of crops than the potato and wheat models introduced above. Nitrogen is not explicitly addressed and it is assumed that weeds and pests do not limit crop yield. Hansen *et al* (1990) present a generalised model of crop growth that includes detailed components relating to soil moisture, temperature, organic matter and nitrogen turnover. Unfortunately, difficulties associated with obtaining data and the smaller range of crops that are addressed compared with Kvifte's model precluded the adoption of Hansen *et al*'s model.

However, some modifications to Kvifte's model are made using equations from Hansen *et al* (1990). This is to allow the effect of temperature on canopy development to be modelled. An assumption of Kvifte's model is that the growth in green leaf area index (GAI) occurs in three distinct stages. During the first of these stages, GAI increases exponentially to a maximum. In the second stage, GAI equals the maximum GAI, and in the final stage GAI declines linearly with time to zero. It is assumed that yield does not change after GAI becomes zero. Kvifte assumes that the times at which these stages commence, are constants, for each of the modelled crops. Hansen *et al* model a similar profile of changes in GAI to Kvifte, but they assume that these stages commence after a given number of degree days have elapsed.

A further modification to Kvifte's model is necessary to account for the influence of crop height on the rate of transpiration (see Equation 7.9.2 in Kvifte (1987)). Kvifte reports a relationship between crop height and wind speed and the resistance to water vapour transport from the canopy surface to a reference height above the crop. However, Kvifte does not specify how changes in crop height are calculated. In the current study, it is assumed that the ratio of a crop's height to the maximum height of a crop is the same as the ratio between GAI and the maximum GAI during the period that GAI is increasing or is at a maximum. In the period prior to harvest when GAI is declining to zero, it is assumed that crop height equals the maximum crop height.

The equations reported in Kvifte (1987) that relate to soil moisture balance are incomplete. It was not possible, therefore, to implement the component of Kvifte's model that associates changes in soil moisture to the water holding capacity of different soils. Hansen *et al* (1990) include a soil water balance model that potentially could have been used in Kvifte's model. However, the inclusion of Hansen *et al*'s soil moisture model would have resulted in a level of model complexity that is inappropriate given the relative simplicity of other components in Kvifte's model. In the current study, a decision was made to not explicitly simulate changes in soil moisture. Rather, in the simulation model, it is assumed that soil moisture does not limit crop yield.

To address the influence of soil water holding capacity on the estimates of potential crop yield within the LP model, adjustments are made to the parameters that are derived from the runs performed with Kvifte's model. Also, parameters relating to potential growth are adjusted to account for the presence of pests, and management factors such as the selection of alternate cultivars that are grown to produce different end products (for example winter feed barley and winter malting barley) or where crops are subjected to management that results in differing yields (such as under sowing spring feed barley). The approach to incorporating the influence of variables which are not explicitly simulated, is less satisfactory than if these variables are addressed in the respective simulation model. However, the adjustments that are introduced did allow factors that are considered important to the objectives of the current study to be included in the LP model. The methods used to make these adjustments and the circumstances that they are employed are discussed below.

In this study it is assumed that the parameters established from Kvifte's model, provide estimates of the potential growth of crops, in the absence of water limitations. The parameters derived from Kvifte's model are assumed, therefore, to be specific to the heaviest of the represented soil types, for each of the crops, climates, regions and planting dates that are considered. In the LP model, the barley crops that are grown for animal feed can be produced on any of the four modelled soils. To address the effect that differences in the water holding capacity have on the productivity of these soils, a REML analysis (Genstat, 1994) is performed on trial data collected from various sites in Scotland.

The REML method estimates the treatment effects and variance components in linear models that are subject to both fixed and random effects. The method is suitable for analyses of unbalanced data sets, and unlike regression analysis, is able to account for more than a single source of variation in a data set. A feature of REML analyses that is particularly useful in the current context is the ability of the technique to make use of information from experiments that are performed at different times or locations (Genstat, 1994; Hunter *pers. comm.*, 1995).

The influence of soil water holding capacity on crop yield is evaluated using data collected from trials reported in a series of annual reports produced by the East of Scotland College of Agriculture and more recently the Scottish Agricultural College[86] (see Appendix 8). The trials selected from these reports provided information relating to the site, year, soil association, rate of nitrogen application, date of sowing and harvesting, and final crop yield. In addition, data that enabled the average water

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[86] After 1990, the annual reports produced by the Scottish Agricultural Colleges were discontinued.

holding capacity of the soil associations to be calculated, was obtained from a database of Scottish soils (MacDonald *pers. comm.*, 1995).

An assumption of the analysis is that the water holding capacity of a soil in a particular trial is the same as the mean water holding capacity of the respective soil association. Although this is a weak assumption (Vinten *pers. comm.*, 1995) it did allow the influence of soil water holding capacity on crop yield to be estimated. The data relating to year of sowing and nitrogen application rates was collected, as these factors varied widely between the trials and it was necessary to estimate the effect of these factors to improve the estimates associated with the influence of soil water holding capacity.

The estimates derived from the REML analysis are used to adjust the estimates of the potential yield of crops grown on the three lightest soils in relation to the heaviest soil considered in the LP model (soil '4'). For the lighter soils, the parameters obtained from Kvifte's model are adjusted as the product of the difference in the water holding capacity of the respective soil and that of soil '4', and the REML estimate of the influence of water holding capacity on crop yield.

The potential yield of crops that are grown to produce animal feed are further adjusted to reflect reductions in crop yield that are associated with pests. The method of calculating yield reductions that are due to pests, and also the influence of pesticide applications and weeds on crop growth is the same as that used to determine winter feed wheat growth. The actual estimates of potential yield and the adjustments that are made to reflect soil related differences in potential productivity, are discussed in the sections dealing with the respective crops. Estimates of the effect of weeds, pests and pesticides are presented in the relevant sections.

The crops winter malting barley, vining peas and oilseed rape are grown to produce human feedstuffs. In the LP model, these crops are planted on the two heaviest soil types and it is assumed that moisture availability does not restrict crop yield on these soils. Further, on these crops it is assumed that pesticides are applied at recommended rates and the effects of weeds and pests are not considered.

In common with the AFRCWHEAT2 model (Porter, 1993), Kvifte's model does not differentiate between the yield potential of alternate crop cultivars. In the case of peas and oilseed rape, only a single cultivar is considered. The estimates of pea and rape yield that are established with Kvifte's model are assumed to provide estimates of the potential yield of these crops in the absence of pests, weeds and moisture limitations. With respect to winter barley, two cultivars are represented in the LP model; one that is suitable for production of feed barley and the other for malting barley. It is assumed that the estimates of yield derived from Kvifte's model, are equivalent to the potential yield of feed barley, that is grown under conditions where pests, weeds and moisture are non-limiting. To determine the yield of winter malting barley, the estimates from Kvifte's model are reduced by an amount equal to an assumed differential between the yield of the winter feed barley and winter malting barley. A similar procedure is used to account for differences between spring feed barley and spring feed barley that is undersown with pasture.

The majority of parameters that are used in the adopted simulation model are included at the levels specified by Kvifte (1987). The equations, and where possible, the parameters relating to canopy development are obtained from Hansen *et al* (see Equations 8.1 - 8.4 and Table 8.3 in Hansen *et al* (1990)). The parameters that are varied from the values reported in these sources are presented in Table 5-5. The estimates relating to maximum green leaf area index, maximum height and maximum root length for the various crops (G_m,h_m and L_m) were specified for Scottish conditions by Russell *pers. comm.*, (1995).

The parameter relating to the conversion of gross production from units expressing energy production per m^2 to units of dry matter per m^2 (c_0, g MJ^{-1}) is treated as a constant by Kvifte. The value of c_0 acts as a scaling factor with respect to the yield that is predicted by the model. In the current study this variable was allowed to vary when calibrating the model for Scottish conditions. The values of c_0 in Table 5-5 are estimated by minimising differences between the models predictions of yield and trial data. The other parameters in Table 5-5 are held constant when estimating c_0. The ability of the model to reproduce the results of the Scottish trial data is presented in Section 8.2.

The variables relating to the canopy development of spring barley (Λ_i, Λ_1, Λ_2, Λ_3, Λ_r^L, α_r^L, S_{ai}, W_t^0) were taken from Hansen *et al* (1990). In Hansen *et al*'s model, winter barley is not considered, however the growth and development of winter barley is similar to winter wheat (Russell *pers. comm.*, 1995) for which parameters are reported. It is assumed that the parameters relating to winter wheat provide acceptable estimates for winter barley. Also, parameter estimates for winter sown oilseed rape are not reported by Hansen et al. To overcome this shortcoming parameters relating to the development of spring oilseed rape are used. However, when evaluating the model against Scottish trial data the crop consistently matured between one and two months before harvesting. The estimate of Λ_3 was therefore increased from Hansen *et al*'s estimate of 1800 to 2400. In Hansen *et al*'s report, vining peas are not considered. Of the crops that are modelled by Hansen *et al* it was assumed that spring sown barley most closely corresponds to vining peas. The parameter values that relate to the timing and duration of the development stages of vining peas were therefore set to equal the values reported for spring barley. Although, clearly spring barley and vining peas are very different crops, the resulting model of pea growth performed reasonably well during model evaluation (see Section 8.2.1).

The parameters relating to the development of crops are important with respect to predicting crop yields for the regions, climates and sowing dates that are included in this study. The uncertainties regarding the accuracy of these parameters, however, places constraints on the conclusions that can be reached regarding the estimated productivity's of the different scenarios. The uncertainty associated with the crop development parameters is complicated, not just by the absence of estimates for the crops considered in this study, but also because the parameters recorded by Hansen *et al* are estimated for conditions and cultivars in Denmark. Although the models were tested against a wide range of Scottish trial data, the climatic conditions associated with the trials exhibits a smaller range of variation than the scenarios for which yield estimates are required. The results of the model evaluation process suggest that the models perform acceptably for current Scottish conditions but caution must be advised when interpreting the outputs of the simulation models for the regions and climate change scenarios that are included in this study.

Table 5-5. Parameters for Generalised Crop Model.

Parameter[87]	Definition	Spring Barley	Winter Barley	Winter Oilseed Rape	Vining Peas
G_m (m^2 m^{-2})	Maximum green leaf area index. (see Equation 7.6, Kvifte (1987)).	4.2	8.0	6.0	5.0
h_m (m)	Maximum height of crop (2).	0.8	0.8	1.4	1.2
L_m (m)	Maximum root length. (see Equation 7.15.2, Kvifte (1987))	1.0	1.2	1.2	0.8
c_0 (g MJ^{-1})	Convert potential gross production to dry matter. (see Equation 7.8.1, Kvifte (1987)).	52.0	80.0	54.0	37.0
Λ_i (°C)	Canopy development parameter (see Equation 8.1, Hansen *et al* (1990))	400.0	500.0	500.0	400.0
Λ_1 (°C)	Canopy development parameter (see Equation 8.1, Hansen *et al* (1990).	200.0	100.0	125.0	200.0
Λ_2 (°C)	Canopy development parameter. (see Equations 8.3 and 8.4, Hansen *et al* (1990)).	450.0	450.0	450.0	450.0
Λ_3 (°C)	Canopy development parameter (see Equations 8.1 - 8.4, Hansen *et al* (1990))	1550.0	1800.0	2400.0	1550.0
Λ_r^L (°C)	Green crop area index damping parameter (see Equation 8.3, Hansen *et al* (1990))	1450.0	1000.0	400.0	1450.0
α_r^L (°C^{-1})	Green crop area index damping parameter (see Equations 8.3 - 8.4, Hansen *et al* (1990))	3.0	1.8	1.25	3.0
S_{ai} (m^2 kg^{-1})	Specific green crop area index (see Equations 8.3 - 8.4, Hansen *et al* (1990))	20.0	14.0	18.0	20.0
W_t^0 (kg m^{-2})	Canopy development parameter (see Equation 8.2, Hansen *et al* (1990))	0.02	0.02	0.02	0.02
1 Sowing Dates 2 3	See text.	Mar 15 Apr 15 May 15	Sep 15 Oct 15 Nov 15	Jul 15 Aug 15 Sep 15	Mar 15 Apr 15 May 15
Harvest Date	See text	Sep 15	Aug 15	Aug 15	Sep 15

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[87] Parameters are named using the conventions of Kvifte (1987) and Hansen *et al* (1990).

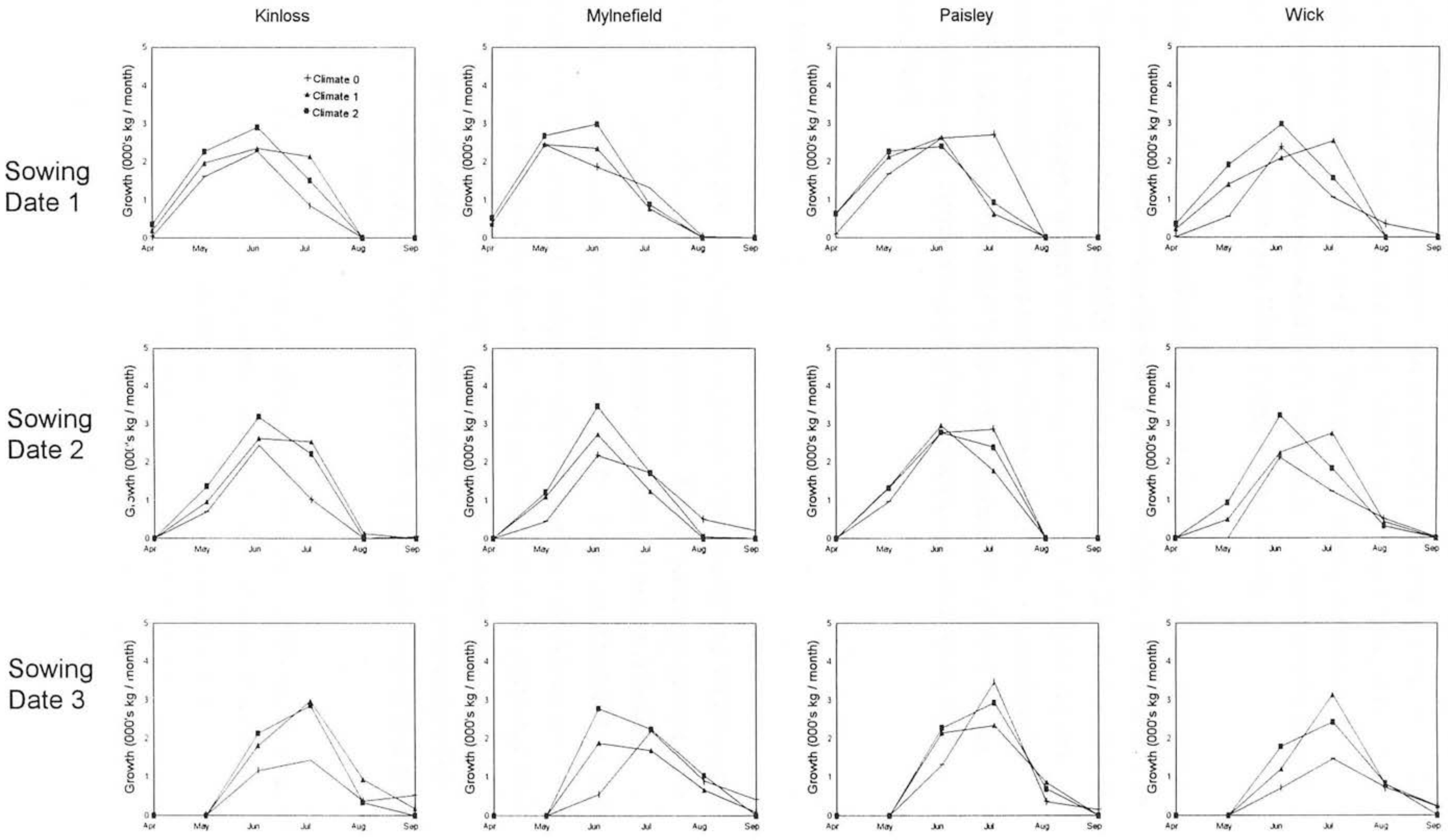
5.3.5.1 Spring Barley.

Estimates of the potential yield of spring feed barley planted on soil '4' are presented in Figure 5-10. The annual estimates of potential production, and the significance of differences between the current and altered climates can be found in Appendix 6. It should be noted that the presented data has been adjusted to reflect the incidence of weeds and pests. The REML analysis that was performed to determine the effect of soil water holding capacity on crop yields showed no significant differences between soils. It is not necessary therefore to differentiate between barley crops that are grown on different soils. With respect to differences between spring feed barley and spring feed barley that is under sown with pasture, a yield penalty of 500 kg per hectare (Barton *pers. comm.*, 1995) is attached to undersown crops. It is assumed that the temporal allocation of the yield reduction associated with undersowing is proportional to the yield estimates in each of the modelled periods.

Under current climatic conditions, Paisley is the most productive of the regions considered, and Wick is the least productive; Mylnefield and Kinloss are intermediate to the other regions. For all of the regions, a reduction in yield occurs when sowing dates are delayed. The extent of this reduction ranges from 25 percent at Paisley to 32 percent at Mylnefield, when planting is delayed from sowing date '1' until sowing date '3'. A change in the sowing date also alters the pattern of monthly increments in yield. For sowing date '1', the peak rate of growth tends to occur in May or June. This compares with June or July for sowing dates '2' and '3'. By delaying the sowing date, the maximum growth rate that occurs, is in some cases higher than those achieved for the earliest sowing date. But in general the increase in peak growth rates that occur with later sowing dates are insufficient to overcome the yield disadvantage of a shorter growing season.

With the exception of sowing date '1' at Paisley, small, non-significant reductions in yield occur at Mylnefield and Paisley, with a change from climate '0' to climate '1'. For sowing date '1' at Paisley, the reduction in yield with a change in climate is significant. At Kinloss and Wick, the most northerly of the regions, yield increases significantly with a change in conditions from climate '0' to climate '1'. The average increase in yield, between climates '0' and '1', for all of the regions is

Figure 5-10. Potential Growth of Spring Feed Barley. (see a2 in Equation 5-2)



approximately 900 kg per hectare or 20 percent. For climate '1', the pattern of changes in yield with delays in sowing date are similar to the changes that occur for climate '0'. An exception to this is Paisley, where the yield for sowing date '1' is intermediate to sowing dates '2' and '3'. The regional ranking in productivity is different for climate '1' than for climate '0'. For climate '1', Kinloss is the highest yielding region, and is followed by Wick, Paisley and Mylnefield.

With respect to changes in production between climates '0' and '2', at Paisley a significant reduction in yield occurs for sowing date '1', while for sowing date '3', a significant increase in yield is recorded. There is no significant difference in yield at Paisley, between climates '0' and '2' for sowing date '2'. For the other regions, significant increases in yield occur on each of the sowing dates. On average the extent of this increase is 1700 kg per hectare or 35 percent. For climate '2', the potential yield of spring barley is highest at Mylnefield and is followed by Kinloss, Paisley and Wick.

5.3.5.2 Winter Barley.

The estimates of the potential production of winter feed barley and winter malting barley are included in Figure 5-11 and Appendix 6. The presented parameters have been adjusted to reflect limitations that arise due to pests and the water holding capacity of the various soils. In the case of malting barley, it is assumed that the crop is weed and pest free, and that the crop can only be grown on soils that are non-limiting in terms of water holding capacity. The parameters that are established from the runs performed with Kvifte's model for malting barley, are adjusted to reflect differences in the yield of feed versus malting varieties. In the current analysis the yield of malting barley is taken to be 500 kg per hectare less than a crop of feed barley (Barton *pers. comm.*, 1995).

From the REML analysis of the effect of soil water holding capacity on the yield of winter feed barley, the mean increase in yield with an increase in water holding capacity is 21.5 kilograms per millimetre of soil water holding capacity (s.e. = 5.3). This corresponds to a difference in yield of approximately 1300 kg per hectare between the lightest and the heaviest soil types. The adjustments to the potential yield of winter feed barley that are made to reflect the influence of pesticide applications are discussed in Section 5.3.8.

Because of the method used to estimate the potential yield of winter barley crops the following discussion is relevant to both feed and malting crops. Given the current climatic conditions, the regions in descending order of productivity are Paisley, Mylnefield, Kinloss and Wick. Between the most and least productive of the regions, there is a difference of approximately 27 percent in average yield. For winter sown crops of barley, there is a tendency for higher yields to occur with later sowing dates. The average increase in yield, between the earliest and latest of the sowing dates, is approximately 15 percent. The largest increase in yield with a delay in sowing date occurs at Paisley, where a 26 percent increase in yield is recorded. The smallest increase is recorded at Mylnefield where the difference in yield is 9 percent.

With the exception of sowing date '3' at Kinloss, there is a significant yield decrease for all regions and sowing dates between climate '0' and climate '1'. For sowing date '3' at Kinloss, there is a reduction in yield, but this is not significant. The average decrease in yield, between climates '0' and '1', is 40 percent. This corresponds to a difference of approximately 2440 kg in harvestable yield. The largest reduction in yield occurs at Paisley, where the decline in yield is 54 percent while the smallest reduction occurs at Kinloss, where yield declines by approximately 32 percent. For climate '1', the most productive region is Mylnefield and the least productive is Wick. The increase in yield associated with later sowing, is greater for climate '1', than for climate '0'. The yield for sowing date '3', averages 56 percent more than for sowing date '1'.

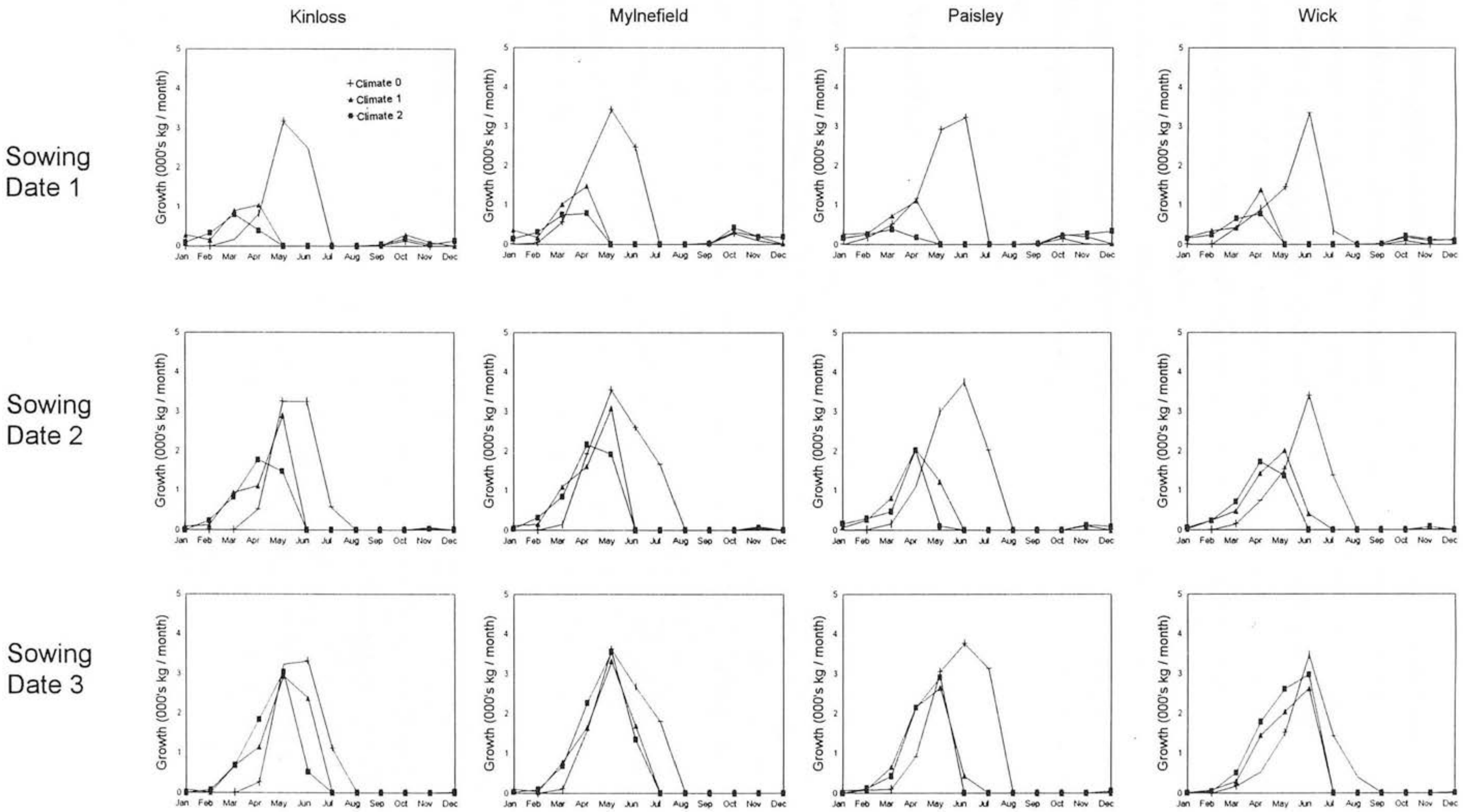
The changes in yield that occur between climates '0' and '2' are similar to those occurring between climates '0' and '1'. There is a significant reduction in average yield for all of the regions and sowing dates between climates '0' and '2'. There is also a greater relative difference in yield between the earliest and latest sowing date for climate '2', than for climate '0'. The extent of the reduction in yield, and also the sensitivity of crop yield to sowing date, is on average greater for climate '2' than climate '1', when compared with climate '0'. An exception to this occurs at Wick, where the average yield is greater for climate '2' than for climate '1'. For climate '2', the ranking of the regions in terms of productivity is: Mylnefield, Wick, Kinloss and Paisley. This contrasts with climate '0', where Paisley is the most, rather than the least, productive region. The estimates for Mylnefield appear to be less sensitive to climate than at Paisley.

The changes in the estimates of crop productivity for different regions and sowing dates, mean that it is likely that current patterns of winter barley production will vary, if climatic changes similar to climates '1' or '2' eventuate. The estimated reductions in yield that occur with a change in climate, suggest that a decline in the production of winter barley will occur in Scotland. This is particularly the case as the estimated productivity's of the other cereal crops in the model (that is winter wheat and spring sown barley), are less detrimentally effected by changes in climatic conditions.

A possible reason for the sensitivity of winter barley to climate is related to the increased temperatures that are associated with the climate change scenarios. As mentioned previously, changes in GAI are simulated as a function of accumulated degree days. The warmer the temperature, therefore, the quicker a crop develops. When a crop achieves maturity, it is assumed that growth of harvestable yield ceases, even if other environmental factors, such as light and moisture are suitable for continued growth. In the case of winter barley, the more rapid crop development that occurs with warmer temperatures, can be to the detriment of the final yield of the crop. Although a reduction in yield associated with a change in climate is plausible with respect to the influence of temperature on winter barley (MacKerron *pers. comm.,* 1995), two factors suggest that the magnitude of the estimated yield reductions need be considered with caution.

Firstly, the trend for higher yields to occur with later sowing dates suggests that the optimal time of sowing, may be later than the dates considered in this study. If additional planting dates are considered in the model, the yield reductions associated with a change in climate, may be less than those estimated in this study. A related point is that farmers may need to make greater adjustments to the management of winter sown crops, in response to a change in climate than for other crops.

Figure 5-11. Potential Growth of Winter Feed Barley (see a2 in Equation 5-2)



Secondly, the quality of data relating to the number of degree days that must be accumulated for the crop development stages to be initiated is of a poor order. Although the model was subjected to a validation process and performed reasonably well, the model is predicting yields for climatic conditions beyond the range that the model has been tested for. As a further point the potential for errors in estimating the transition of winter sown barley and oilseed rape, from one development stage to another is greater than for spring sown crops. This is due to the greater length of time that winter crops are growing in a field. The estimated changes in the productivity of winter barley and oilseed rape with changes in climate may be reasonable, however, less confidence can be placed in these estimates than for spring planted crops.

5.3.5.3 Vining Peas.

The estimates of the potential production of vining peas are included in Figure 5-12 and Appendix 6. As previously mentioned, vining peas are permitted to grow on the two heaviest soils included in the model (soils '3' and '4'). It is assumed, therefore, that soil moisture does not limit the growth of vining peas. Also, the effects of soil nitrogen, pests and weeds are not explicitly modelled. The scenarios that are considered when establishing the parameters to be included in the LP model are three climates, ten years, two soil type, and three planting dates. The factors that are assumed to limit yield, and the climatic scenarios that are considered, are the same for vining peas and potatoes.

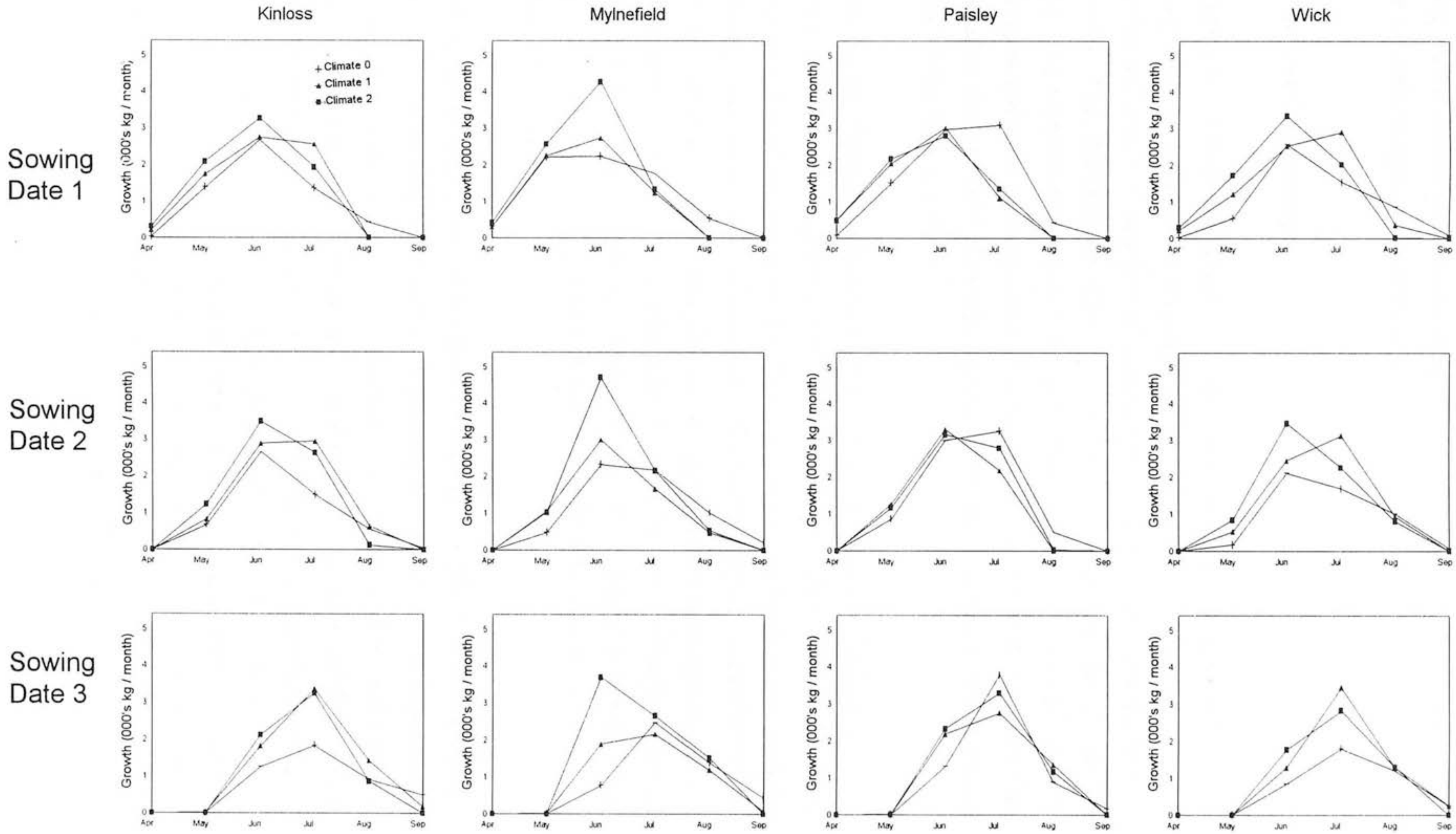
For the current climate, Paisley is followed by Mylnefield, Kinloss and Wick in descending order of yield. The average yield at Paisley is approximately 7300 kg per hectare, which is 32 percent or 2350 kg greater than the yields estimated for Wick. From the presented data it can be seen that higher yields are achieved with earlier planting dates. The differences in yield that can be attributed to delaying planting from sowing date '1' to sowing date '3', range from approximately 1990 kg at Mylnefield to 1360 kg at Kinloss. These represent reductions of 28 and 23 percent, respectively. The two climate change scenarios are less sensitive to delays in planting, than climate '0', as a similar comparison for climate '1' results in yield decreases ranging from 1200 kg at Mylnefield to 345 kg at Paisley. For climate '2', the reductions in yield that are associated with sowing date, vary between 1485 kg at Wick and 14 kg at Paisley.

For climate '1', the productivity's of the regions are ranked in descending order as follows: Kinloss, Wick, Paisley and Mylnefield. The yield differential between the most and least productive regions is smaller for climate '1' than for climate '0'. Between Kinloss and Mylnefield, the difference in average yield is approximately 1090 kg or 15 percent of the yield at Kinloss. At Kinloss, the average yield of vining peas for climate '1' is 7110 kg. The estimated yields at Kinloss and Wick are significantly higher for all sowing dates than the estimates for climate '0'. At Paisley, yield is significantly higher for the first two sowing dates. For the third sowing date, a non-significant increase in yield is recorded and at Mylnefield a non-significant decrease in yield occurs for the earliest sowing date. There is no change in yield for sowing date '2', and for sowing date '3' a non-significant increase is recorded.

For climate '2', Mylnefield is the most productive region, and Wick is the least productive. The average yields at Kinloss and Paisley lie between Mylnefield and Wick. The average yield at Mylnefield is 8300 kg and compares with 6900 kg at Wick. While there is a relatively large difference between Mylnefield and the other regions, differences between the three lowest producing regions are relatively small. With the exception of sowing dates '1' and '2' at Paisley, there is a significant increase in yield between climate '2' and climate '0', for all regions and sowing dates. At Paisley, for sowing dates '1' and '2', a significant and a non-significant reduction in yield, respectively, are recorded between climate '2' and climate '0'.

In general, the difference between regions and sowing dates tend to be less for the climate change scenarios (climates '1' and '2') than for climate '0'. However, there are a number of differences between climates '1' and '2'. For the majority of regions and sowing dates, the yields estimated for climate '2' are higher than climate '1'. The largest difference in yield between climate '1' and '2' is recorded for Mylnefield. The average of this difference is 2280 kg, which is sufficiently large for Mylnefield to improve its ranking from being the least productive region for climate '1', to the most productive region for climate '2'. This outcome is somewhat surprising given the similarity of climates '1' and '2' and also because yield differences between these

Figure 5-12. Potential Growth of Vining Peas (see a2 in Equation 5-2)



climates are relatively small for other regions. The result for Mylnefield suggests that depending on the climate that evolves, differences in productivity may be quite sensitive to small changes in weather patterns.

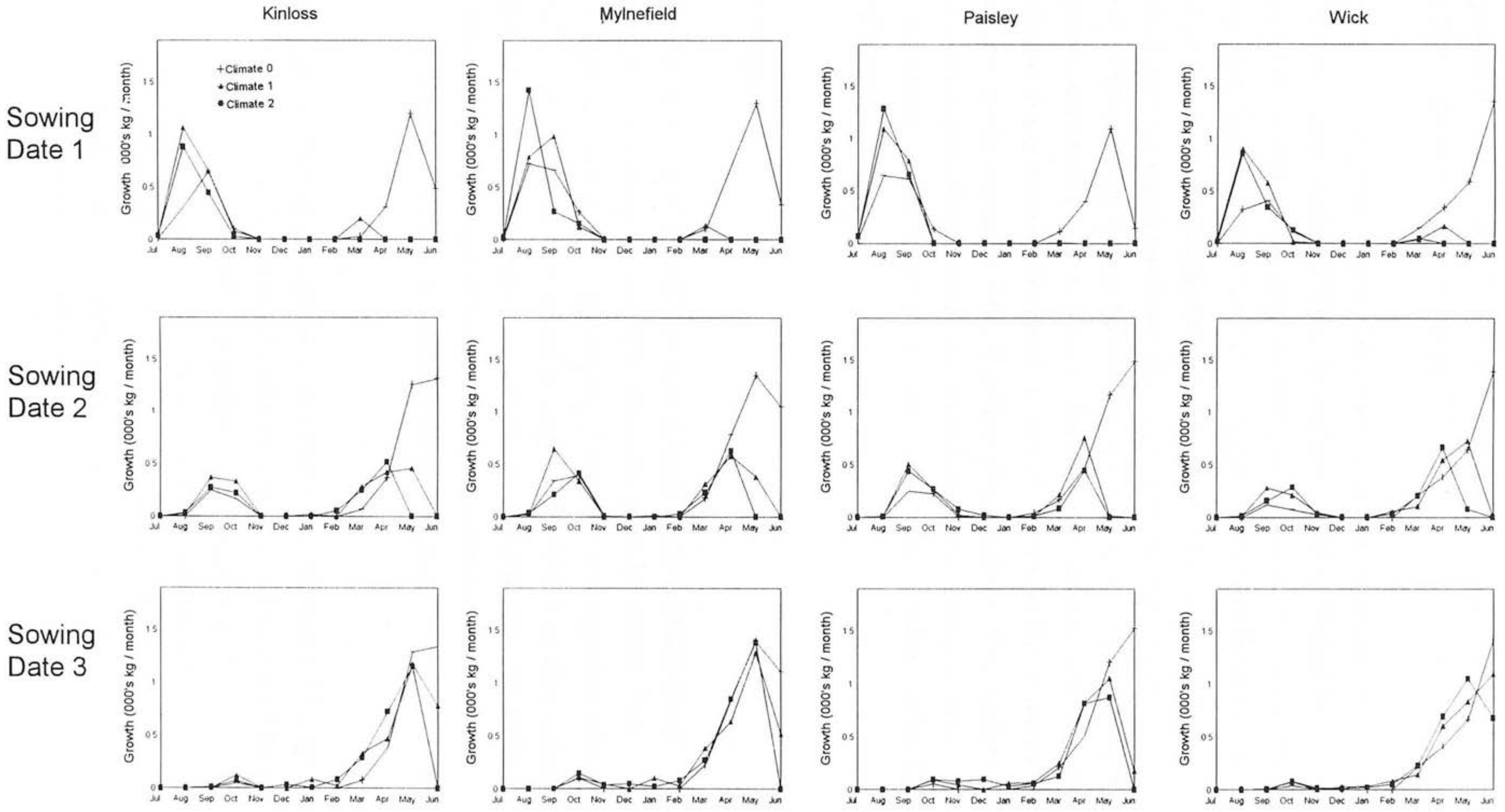
5.3.5.4 Winter Oilseed Rape.

The estimates of the potential yield of winter oilseed rape are included in Figure 5-13 and Appendix 6. As for other crops that are only permitted to be grown on the two heaviest soils (soils '3' and '4'), it is assumed that soil moisture does not limit crop growth. Also, the influence of pests and weeds on crop growth are not explicitly modelled. The scenarios that are considered are three climates, ten years of weather, two soil types, and three planting dates. The climatic scenarios and the variables that are assumed to limit the yield of oilseed rape, are the same as those for winter malting barley and winter milling wheat.

For the current climate, the highest potential yield estimates are obtained at Mylnefield, and the lowest estimates at Wick. The average yield at Mylnefield is 3965 kg per hectare. The difference in yield between Mylnefield and Wick is approximately 1,000 kg or 26 percent of the yield achieved at Mylnefield. Between climates '0' and '1', there is a significant reduction in yield for all regions and all plantings performed on sowing dates '1' and '2'. For sowing date '3', at Mylnefield and Paisley, there is a significant reduction in yield between climates '0' and '1'. A similar comparison for sowing date '3' shows a non-significant reduction in yield at Kinloss and a non-significant increase at Wick.

For all of the climates, the most productive region is Mylnefield. The ranking of lower yielding regions changes, however, depending on the climate that is considered. For climate '1', Kinloss and Wick, are second and third in productivity, and Paisley is the least productive region. The average yield of oilseed rape grown at Mylnefield is 2490 kg, and compares with 2110 kg at Paisley. The difference in average yield between Mylnefield and Paisley is 380 kg or 15 percent of the yield at Mylnefield. Although the average yields of crops for climate '1' are lower than those obtained for the base climate, there is a smaller difference in yields between the regions for climate '1' than for climate '0'. For climate '2', the regions can be ordered as follows : Mylnefield, Wick, Paisley and Kinloss, with Kinloss being the least productive region. For climate '2', the average yield at Mylnefield is 2100 kg,

Figure 5-13. Potential Growth of Winter Oilseed Rape (see a2 in Equation 5-2)



and at Kinloss the average yield is 1710 kg. This represents a difference of 19 percent. In general the yield levels achieved for climate '2', are lower than those for crops grown under either climate '0' or climate '1'.

The influence of sowing date on crop yield varies between regions and climates. For climate '0', with the exception of Wick, the maximum yield is obtained by planting crops on the second sowing date. At Wick, the highest yield occurs on the earliest sowing date. For climates '1' and '2', the highest yields are achieved from crops planted on the last of the sowing dates. From Figure 5-13 it can be seen that during the initial period of crop growth that differences between climates are relatively small. Differences in the growth of oilseed rape, appear to occur principally during the months immediately prior to harvest. Further, differences between climate '0' and the climate change scenarios (climates '1' and '2'), that arise during the period before harvest, are greater for earlier rather than later planting dates. This suggests that the more rapid crop development that occurs with the warmer temperatures associated with climates '1' and '2' results in crop growth being penalised during the later stages of growth.

5.3.6 Soil Nitrogen.

The methods used to describe the influence of nitrogen on the productivity of farming systems has a significant impact on the structure of the LP model. The activities that represent crop growth, applications of inorganic and organic fertiliser, cropping rotations, crop residue disposal and grazing are formulated to allow changes in the availability of nitrogen during the growing season to be modelled. To achieve this it is necessary to specify a relatively large number of parameters to account for changes in nitrogen status and the likely implications of these changes on farm system productivity.

With the exception of vining peas, potatoes and swedes (see Section 5.2.1), the growth of crops that are included in the LP model are assumed to be restricted by soil nitrogen to be less than or equal to potential growth. The estimates of crop requirements for nitrogen and the turnover of nitrogen in soil are obtained from a range of sources in the literature. In the current study, variations in soil productivity are assumed to be a function of the available water holding capacity of the soil. It is assumed that the productivity of soils are not directly influenced by differences in the rates of processes that affect the turnover of nitrogen. Although the moisture status of a soil is likely to influence the rates of mineralisation and losses of nitrogen from a soil (Addiscott, 1983; Addiscott and Whitmore, 1987 and 1991; Beek and Frissel, 1973; Jannson *et al*, 1988; Scholefield and Rodda, 1992), the temporal and spatial aggregation of the LP model is not appropriate for considering detailed variations in the cycling of nitrogen.

In the sections below the parameters and assumptions relating to the turnover of nitrogen in soils are discussed. In the first section, parameters that relate to the cycling of nitrogen in soils are presented. In the following section, the influence that crops and weeds have on the nitrogen status of soils is considered. In the final section, parameters that represent the influence of management factors such as the cropping rotation, method of residue disposal and applications of fertiliser and farm yard manure are presented.

5.3.6.1 Cycling of Nitrogen in Soils.

The processes that are considered in this model are atmospheric deposition, net mineralisation, denitrification, volatilisation, and leaching to groundwater. As mentioned in Section 5.2.4, it is assumed that the rate of mineralisation, denitrification and volatilisation are functions of temperature and can be calculated using an arrhenius equation (see Equation 5-19). The rate of atmospheric deposition of nitrogen is assumed to be proportional to rainfall (Vinten *pers. comm.*, 1995). With respect to leaching of nitrogen, it is assumed that losses occur during autumn and winter months when growth of crops is least vigorous. At other times of the year it is assumed that losses of nitrogen due to leaching are negligible (Addiscott, 1977; Addiscott and Bland, 1988; Addiscott *et al*, 1991; Simonis, 1988; Spiers *pers. comm.*, 1995). During the period that leaching is considered the monthly distribution of leaching is assumed to be proportional to rainfall. The parameters associated with the cycling of nitrogen in soils are estimated for each region and climate and it assumed that these parameters do not vary between soil types.

The parameters a21 and a22, from Equation 5-17, that represent atmospheric deposition and net mineralisation of nitrogen are presented in Table 5-6 and Table 5-7. From Aslyng and Hansen (1982) the atmospheric deposition of nitrogen is assumed to be 20 kg per year, and the net mineralisation of nitrogen is taken as 50 kg per year. These values are similar to those reported by Scholefield *et al* (1991) and concord with expected levels for Scottish conditions (Vinten *pers. comm.*, 1995). It is assumed that the annual amount of nitrogen that is derived from these sources does not vary between the different regions or climates that are considered.

In the LP model, the parameter a14 (see Equation 5-15) is fitted to provide an estimate of the losses of nitrogen from soil. The annual losses from denitrification, volatilisation and leaching are assumed to be 20 kg, 10 kg and 40 kg per hectare, respectively (Aslyng and Hansen, 1982; Scholefield *et al*, 1991; Vinten *pers. comm.*, 1995, Vinten *et al*, 1991). As mentioned previously, the temporal distribution of these losses are estimated, respectively, as functions of temperature and rainfall. To determine a14, the sum of denitrification, volatilisation and leaching losses are expressed as a proportion of the quantity of nitrogen that is present in the soil. It is necessary, therefore, to estimate the nitrogen status of soils at different times of the year in the presence of a growing crop. There is relatively little difference in the pattern of nitrogen uptake between the cereal crops. In this study, a crop of spring feed barley, fertilised at recommended levels, is used to perform this calculation. The estimates of a14 are presented in Table 5-8.

5.3.6.2 Crop Uptake, Leaching and Fixation of Nitrogen.

The estimates included in Figure 5-7 that relate to pasture growth refer to the potential production of leaf material. As discussed in Section 5.2.2, production of stem is not explicitly represented in the LP model. The amount of nitrogen required for leaf growth must be adjusted, therefore, to reflect the uptake of soil nitrogen by other plant components. In the current study it is assumed that the net growth of roots in mature pasture is zero (Kvifte, 1987). The uptake of soil nitrogen by growing pasture is determined by multiplying the nitrogen content of leaf by the ratio of leaf and stem growth to leaf growth (see Equation 5-3).

From Dilz (1988) the nitrogen content of plant material is taken as 0.025 kg nitrogen per kg of pasture growth and the ratios of leaf and stem growth are determined from Topp and Doyle's (1994) time series data. The parameters that represent the uptake of nitrogen per unit of leaf growth are presented in Table 5-10. There is little difference between grass and grass / clover with values of a1 (see

Table 5-6. Atmospheric Deposition of Nitrogen (kg hectare^{-1} month^{-1}) (a21, see Equation 5-17)

Region	Kinloss			Mylnefield			Paisley			Wick		
Climate	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’
January	1.7	2.3	1.7	1.4	2.1	1.4	1.9	2.7	1.9	1.7	2.1	1.7
February	1.5	2.0	1.5	2.1	2.4	2.1	2.4	2.1	2.4	1.8	2.3	1.8
March	1.6	1.8	1.6	2.1	1.9	2.1	1.8	1.5	1.8	1.8	1.7	1.8
April	1.4	1.3	1.4	1.7	1.8	1.7	1.6	1.3	1.6	1.7	1.6	1.7
May	1.4	1.4	1.4	1.2	1.2	1.2	0.9	1.3	0.9	1.4	1.4	1.4
June	2.3	1.7	2.3	1.4	1.4	1.4	1.4	1.2	1.4	1.2	1.3	1.2
July	1.7	1.1	1.7	1.4	1.0	1.4	1.4	1.3	1.4	1.3	1.1	1.3
August	1.6	1.4	1.6	1.4	1.3	1.4	1.4	0.9	1.4	1.4	1.0	1.4
September	1.6	1.3	1.6	2.2	1.4	2.2	1.9	1.5	1.9	1.9	1.3	1.9
October	1.8	1.9	1.8	1.8	2.2	1.8	1.6	2.3	1.6	2.0	2.2	2.0
November	1.5	2.2	1.5	1.8	1.7	1.8	2.3	2.0	2.3	2.0	2.0	2.0
December	1.6	1.8	1.6	1.4	1.6	1.4	1.4	2.0	1.4	1.7	2.1	1.7

Table 5-7. Net Mineralisation on Nitrogen in Soils (kg hectare^{-1} month^{-1}) (a22, see Equation 5-17)

Region	Kinloss			Mylnefield			Paisley			Wick		
Climate	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’
January	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.5	2.6	2.6
February	2.4	2.3	2.3	2.2	2.3	2.3	2.3	2.3	2.3	2.5	2.4	2.4
March	2.6	2.8	2.8	2.9	2.8	2.8	2.7	2.7	2.7	2.8	2.8	2.8
April	3.8	3.7	3.7	3.4	3.8	3.8	4.0	4.1	4.1	3.4	3.7	3.7
May	5.5	5.3	5.3	5.0	5.2	5.2	5.4	5.4	5.4	4.7	4.6	4.6
June	7.0	6.8	6.8	7.5	6.8	6.8	6.8	7.1	7.1	6.0	5.9	5.9
July	7.7	7.9	7.9	7.6	8.1	8.1	7.8	8.3	8.3	7.2	6.8	6.8
August	7.3	7.5	7.5	8.1	7.7	7.7	7.8	7.1	7.1	7.0	7.2	7.2
September	6.0	6.0	6.0	6.5	5.8	5.8	6.3	6.3	6.3	5.7	5.9	5.9
October	4.5	4.9	4.9	4.7	4.4	4.4	4.7	4.5	4.5	4.8	4.7	4.7
November	3.5	3.3	3.3	3.2	3.4	3.4	3.1	3.1	3.1	3.7	3.7	3.7
December	2.5	2.4	2.4	2.4	2.6	2.6	2.4	2.5	2.5	3.0	2.9	2.9

Equation 5-3) ranging between 0.034 and 0.036. This corresponds to a difference of approximately 5 percent, with the lowest values of a1 occurring during the winter months.

The leaching of nitrogen from dead plant material is an important pathway for nitrogen to cycle between pasture and soil sub-systems. It is assumed that 35 percent of the nitrogen that is present in dead pasture is leached in a mineral form and becomes available for subsequent growth (Nielsen *et al*, 1988). The amount of nitrogen that is returned to the soil in a particular period is estimated as the product of the nitrogen content of leaf, the fraction of nitrogen that is leached, and the amount of leaf plus stem material that dies. The relative amounts of leaf and stem material that die in each period are determined from Topp and Doyle's time series data.

It is assumed that the amount of nitrogen that is fixed in grass / clover pastures is 200 kg per year Watson *et al* (1992). The temporal distribution of nitrogen fixation is calculated for each climate and region, but it is assumed that the total amount of nitrogen does not vary between these scenarios. In Topp and Doyle's (1994) model, fixed nitrogen is calculated as a function of the leaf area index of clover, so that variations in the abundance of clover affect nitrogen fixation. Although Topp and Doyle report changes in the amount of clover that are present in the sward with changes in climate and regions, the extent of these differences is small. The estimates of nitrogen fixation for grass / clover swards are presented in Table 5-9.

With respect to arable crops, the LP model accounts for growth of harvestable yield (see Section 5.2.2). To determine the total uptake of nitrogen by the crop, the nitrogen content of the harvestable fraction of the crop is adjusted to reflect the uptake of nitrogen by non-harvested components of the crop. These include leaf, stem and root material. In the case of winter wheat crops, the AFRCWHEAT2 model considers the growth and development of leaf, stem, roots and grain. The values of a1 (see Table 5-10) are determined by dividing the total amount of nitrogen taken up by the crop each month by the growth in harvestable yield. The values of a1 for wheat range from 0.08 during the initial stages of crop growth to 0.02 during the months before harvest. When evaluating the winter wheat time series data it was found that on average crop dry matter contained 4 percent of nitrogen until early May. After this time there is a steady decline in the nitrogen content of the crop to 1.5 percent.

Table 5-8. Proportion of Mineral Nitrogen that is Lost from Soil due to Denitrification, Volatilisation and Leaching (fraction) (a14, see Equation 5-15)

Region	Kinloss			Mylnefield			Paisley			Wick		
Climate	'0'	'1'	'2'	'0'	'1'	'2'	'0'	'1'	'2'	'0'	'1'	'2'
January	0.075	0.084	0.076	0.059	0.078	0.059	0.073	0.091	0.073	0.070	0.079	0.071
February	0.072	0.080	0.071	0.083	0.093	0.083	0.091	0.079	0.091	0.075	0.089	0.075
March	0.046	0.045	0.046	0.052	0.047	0.051	0.044	0.038	0.044	0.046	0.042	0.046
April	0.019	0.020	0.020	0.019	0.021	0.021	0.021	0.023	0.023	0.017	0.020	0.020
May	0.042	0.043	0.046	0.044	0.047	0.048	0.041	0.047	0.048	0.030	0.035	0.037
June	0.066	0.070	0.080	0.079	0.078	0.110	0.069	0.082	0.081	0.050	0.055	0.067
July	0.074	0.104	0.109	0.089	0.096	0.143	0.112	0.097	0.101	0.064	0.085	0.092
August	0.065	0.090	0.093	0.088	0.084	0.121	0.101	0.078	0.080	0.061	0.083	0.088
September	0.143	0.150	0.199	0.199	0.139	0.284	0.213	0.146	0.184	0.140	0.140	0.200
October	0.147	0.182	0.212	0.163	0.181	0.243	0.175	0.173	0.148	0.140	0.188	0.199
November	0.123	0.192	0.175	0.153	0.143	0.245	0.215	0.151	0.181	0.136	0.168	0.197
December	0.126	0.165	0.184	0.126	0.134	0.206	0.149	0.152	0.127	0.121	0.177	0.178

Table 5-9. Nitrogen Fixation by Grass / Clover (kg hectare^{-1} month^{-1}) (a20, see Equation 5-17)

Region	Kinloss			Mylnefield			Paisley			Wick		
Climate	'0'	'1'	'2'	'0'	'1'	'2'	'0'	'1'	'2'	'0'	'1'	'2'
January	8.3	8.5	8.5	8.3	8.5	8.5	8.4	8.3	8.3	10.0	10.4	10.4
February	9.5	9.4	9.4	8.8	9.2	9.2	9.1	9.1	9.1	9.9	9.7	9.7
March	10.6	11.0	11.0	11.8	11.1	11.1	10.7	10.8	10.8	11.3	11.4	11.4
April	15.1	15.0	15.0	13.7	15.1	15.1	16.0	16.3	16.3	13.6	14.8	14.8
May	22.0	21.2	21.2	20.0	20.8	20.8	21.4	21.5	21.5	18.8	18.5	18.5
June	28.1	27.2	27.2	30.2	27.1	27.1	27.1	28.3	28.3	24.1	23.6	23.6
July	30.7	31.6	31.6	30.5	32.2	32.2	31.2	33.2	33.2	28.8	27.2	27.2
August	29.1	30.0	30.0	32.6	30.9	30.9	31.2	28.6	28.6	27.9	28.7	28.7
September	24.1	24.1	24.1	26.1	23.0	23.0	25.3	25.4	25.4	22.8	23.6	23.6
October	18.2	19.6	19.6	18.7	17.5	17.5	18.9	18.1	18.1	19.0	18.9	18.9
November	13.8	13.2	13.2	12.8	13.8	13.8	12.6	12.2	12.2	14.9	14.6	14.6
December	10.1	9.5	9.5	9.6	10.4	10.4	9.5	9.9	9.9	12.1	11.6	11.6

The growth of other crops, for which parameters relating to the nitrogen content of the plant are required, are estimated using Kvifte's (1987) model. These include spring barley, winter barley and winter oilseed rape. However, as previously mentioned, Kvifte's (1987) model does not account for the uptake of soil nitrogen. In the current study, it is assumed that the nitrogen content of arable crops is described using the following equation from Greenwood (1986).

$$\%N = 1.33 + e^{(1.4 - 0.26W)} \quad (5\text{-}19)$$

where W is the total plant dry weight (tonnes hectare^{-1}); and %N is the percentage of the dry weight of a crop accounted for by nitrogen. Greenwood suggests that the equation provides acceptable estimates of the nitrogen content of a wide range of different crops. Equation 5-20 may, however, understate the amount of nitrogen that is taken up by a growing crop. A number of studies have shown that losses of nitrogen occur as crops mature (Houba, 1973; Legg and Meisinger, 1982; and Tukey, 1970). Equation 5-20 was originally estimated from experiments that measured nitrogen content at harvest. Losses of nitrogen that occur during the growing season may therefore lead to discrepancies between the amount of nitrogen that is taken up by a crop and the amount of nitrogen that is present at harvest.

In contrast to these results, Siman (1974) found that the nitrogen content of a growing crop can be predicted closely by Equation 5-20. In this study, Equation 5-20 is used to estimate the uptake of nitrogen in crops that are simulated with Kvifte's model. In this study a1 is established by multiplying the ratio of Kvifte's estimates of total crop growth to growth in harvestable yield with the estimates derived from Equation 5-20. The resulting values of a1 are presented in Table 5-10.

For spring and winter barley and oilseed rape, the estimates of a1 decline as the growing season progresses. This is related to two factors. During the initial months of growth, increases in harvestable grain account for a small proportion of total crop growth. As the season progresses the proportion of growth that is attributed to grain increases. This reduces the ratio between the uptake of nitrogen by a growing crop and changes in harvestable yield. The second factor is related to the form of Equation 5-20 which describes a decline in nitrogen content as a crop gets heavier.

From Table 5-10 it can be seen that the values of a1 for spring barley range from 0.439 to 0.002, with higher values of a1 estimated in the earlier months of growth. This corresponds to an uptake of approximately 145 kg of nitrogen or 1.9 percent of the total dry matter of a crop of spring feed barley. For winter barley the values of a1 range between 1 and 0.002. The average uptake of nitrogen by a crop of winter feed barley is 150 kg which equates to 1.8 percent of total crop dry matter. The values of a1 for winter oilseed rape range between 0.41 during the initial months of growth to 0.004 in the months prior to harvest which corresponds to an uptake of nitrogen of approximately 130 kg or 2.2 percent of the crop dry matter.

The leaching of nitrogen from dead plant material from arable crops is not modelled. In this study, it is considered that nitrogen leaching from dead crop material is of less concern than nitrogen leaching from weeds or pasture. The reason for this is that most of the nitrogen that is leached from arable crops, occurs in the months immediately prior to harvest (Greenwood, 1986). The potential for leached nitrogen to have an influence on the subsequent growth of a crop is, therefore, relatively small.

Table 5-10. Nitrogen Requirement for Crop Growth (kg N. kg yield^{-1}) (a1, see Equation 5-1).

Month	Grass / Clover	Grass	Winter Wheat	Spring Barley	Winter Barley	Winter Oilseed Rape
January	0.035	0.034	0.08	-	0.009	0.004
February	0.035	0.035	0.08	-	0.013	0.007
March	0.035	0.035	0.08	0.333	0.014	0.013
April	0.035	0.035	0.08	0.439	0.012	0.010
May	0.036	0.036	0.02	0.391	0.007	0.007
June	0.036	0.036	0.02	0.025	0.005	0.004
July	0.036	0.036	0.02	0.010	0.002	0.289
August	0.036	0.036	0.02	0.005	-	0.358
September	0.036	0.036	0.02	0.002	1.000	0.410
October	0.036	0.036	0.08	-	0.759	0.233
November	0.036	0.036	0.08	-	0.715	0.273
December	0.036	0.035	0.08	-	0.714	0.003

An assumption of this study, is that the nitrogen content of weed biomass is the same as grass. However, the estimates of weed growth in Section 5.3.7 refer to the growth of above ground weed material. To account for the uptake of soil nutrients by weed roots, the amount of root material produced by weeds must be accounted for. As suitable data that refers to weeds could not be found, it is assumed that the quantity of roots produced by weeds is the same as grass. Kohnlein and Vetter (1953) evaluated the quantity of root material produced by a number of crops and report a value of about 1.8 tonnes per hectare for grass. In an experiment on fertilisation and irrigation, Jensen (1980) found that the dry weights of grass roots are between 1.5 and 2.0 tonnes per hectare. It is assumed in this study that the quantity of roots produced by undisturbed weeds is 1.8 tonnes per hectare.

The total amount of weed material that is produced in a field therefore approximately equals 3.0 tonnes per hectare, which corresponds to the amount of above and below ground dry matter. The parameter a1 is estimated by multiplying the ratio of total weed to above ground biomass by 0.025 kg of nitrogen per kg of weed material. This results in a value of a1 of 0.0625 kg N per kg of above ground weed growth. With respect to leaching of nitrogen from dead weed material, it is assumed that 35 percent of the nitrogen contained in dead weed material subsequently becomes available in mineral form. The parameter a18 (see Equation 5-16) is therefore taken as 0.022.

5.3.6.3 Influence of Crop and Pasture Management on Nitrogen Cycling.

In this section the parameters that represent the influence of management factors, such as the choice of cropping rotation and residue disposal on the nitrogen status of soils, are presented. In the LP model, it is assumed that there is a response in nitrogen mineralisation in the first two years following the ploughing of pasture. It is also assumed that the amount of mineralisation that occurs is a function of the age of the pasture (Lloyd, 1992). The method used to model the influence of pasture on subsequent crops involves a pieci-linear representation of the contribution of pasture to nitrogen mineralisation rates.

The assumptions relating to increases in mineralisation rates are estimated from the recommendations included in ESCA (1983), and by assuming that losses of mineral nitrogen are approximately 50 percent in arable systems (Vinten *pers. comm.*, 1995). If pasture is less than four years old when ploughed, it is assumed that in the first crop to follow pasture, 35 kg of nitrogen is mineralised per hectare per year of undisturbed pasture growth. If the pasture is greater than 4 years old, the increase in mineralisation associated with the ploughing of pasture is assumed to be 140 kg per hectare. In the second crop to follow pasture, the amount of nitrogen mineralisation is assumed to be two thirds of the respective rates of the first crop to follow pasture (Lloyd, 1992).

The contribution of other crops and the implications of the method of residue disposal on the mineralisation of nitrogen in crops subsequently planted to the same ground are presented in Table 5-11. It is assumed that cereal crops are the most exhaustive of the represented crops. From ESCA (1983), when cereal straw is baled, it is assumed that there is no net transfer of nitrogen to a following crop. Conversely if the residues of a cereal crop are incorporated, 20 kg of nitrogen per hectare is assumed to be immobilised and hence unavailable to an incoming crop (Catt *et al*, 1992; Rule *et al*, 1991).

With respect to peas, residues are disposed of either by grazing or by incorporation. The residues of potatoes, oilseed rape, and swedes are disposed of by incorporation. It is assumed that for crops following peas, potatoes, oilseed rape and swedes that soil mineralisation rates are increased by 100 kg of nitrogen (McEwan *et al*, 1989; ESCA, 1983). Although the derivation of parameters relating to inter-crop transfers of nitrogen is somewhat arbitrary, the models produced acceptable results when evaluated.

Table 5-11. Amount of Nitrogen Transferred to a Subsequent Crop (kg hectare^{-1})[88].

Crop	Method of Residue Disposal		
	Graze	Incorporate	Bale
Swedes		100	
Potatoes		100	
Spring Feed Barley		-20	0
Spring Feed Barley (under sown with pasture)			0
Vining Peas	100	100	
Winter Oilseed Rape		100	
Winter Feed Barley		-20	0
Winter Malting Barley		-20	0
Winter Feed Wheat		-20	0
Winter Milling Wheat		-20	0

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[88] For estimates relating to grass and grass / clover see section 5.3.6.3.

The influence of grazing on nitrogen cycling is incorporated by assuming that the nitrogen contained in ingested plant material is apportioned between animal product, urine and dung. The assumptions used to estimate a16 (see Equation 5-15) are similar to those used by Scholefield *et al* (1991) who present a model of pasture grazed by beef animals. ARC (1980) report relationships between the percentage of nitrogen retained by animals and the nitrogen content of feed. Pasture is assumed to contain 2.5 percent of N or approximately 3.6 percent N when nitrogen content is expressed per kg of leaf. This corresponds to a retention of approximately 15 percent for medium sized steers gaining a kilogram per day (ARC, 1980). It is assumed that the same value applies to other animal types included in this model. The distribution of excreted nitrogen between urine and dung is calculated on the basis of a linear relationship estimated by Scholefield *et al* (1991). Given Scholefield *et al*'s relationship and the assumed N content of pasture, the proportion of excreted nitrogen that is in urine is estimated as 60 percent.

Further assumptions relating to the excretion of nitrogen are that 15 percent of nitrogen in urine is lost through volatilisation as gaseous ammonia (Lockyer and Whitehead, 1990; Ryden *et al*, 1987; Vertregt and Rutgers, 1987); the remainder of urinary nitrogen is assumed to be available to plants (Thomas *et al*, 1988). Of the nitrogen in dung, it is assumed that 25 percent is readily mineralisable (Mason *et al*, 1981), and the remaining nitrogen in dung is assumed to be held in organic matter and hence unavailable for pasture. Losses due to volatilisation from dung are small (Ryden *et al,* 1987), and these losses are ignored. From these assumptions, and assuming that the ratio of leaf to stem in the animals diet is constant, approximately 50 percent of the nitrogen that is ingested by animals is returned to the soil in a usable form. The value of a16 for both grass and grass / clover is set to 0.018.

The residues of vining pea crops can also be grazed by animals. Similar assumptions as for pasture are used to calculate the amount of nitrogen that is excreted by animals in a form that is usable by a following crop. The nitrogen content of pea straw is assumed to equal 0.7 percent (Staniforth, 1979). Assuming, that at the time of grazing, pea straw is the only constituent of an animals diet, the percentage of ingested nitrogen that is retained by an animal is approximately 36 percent. Of the nitrogen that is excreted, Scholefield *et al*'s relationship suggests that approximately 34 percent is in urine, and the balance is in dung. After calculating the losses of nitrogen from urine and dung, approximately 30 percent of the nitrogen that is ingested in pea straw is returned to the soil. For peas, a16 is taken as 0.002.

To estimate the effect of manure N on soil nitrogen availability, the assumptions associated with a model presented by Beauchamp and Paul (1989) are adopted. Their model adopts a similar approach to that of Scholefield *et al* (1991) in terms of partitioning nitrogen into categories that are subject to differing degrees of loss. In Beauchamp and Paul's model, nitrogen that is present in farm yard manure is assumed to be distributed equally between organic nitrogen and nitrogen that is in the form of ammonia. They estimate that 20 percent of the nitrogen that is present in organic matter is readily mineralisable, and assume that the remaining 80 percent of organic N is not available to plants. Of the ammoniacal nitrogen, 25 percent is assumed to be volatilised; the remaining 75 percent is assumed to become available to crops.

The estimates presented by Beauchamp and Paul suggest that 47.5 percent of the nitrogen in farm yard manure becomes available to crops. The parameters in their model that relate the proportion of ammoniacal and organic nitrogen that are lost are similar to those of Scholefield *et al* (1991). The nitrogen content of farm yard manure is taken as 0.33 percent from Smith (1992). The value of a15 (see Equation 5-15) is calculated as the product of Beachamp and Paul's estimate of the proportion of nitrogen in manure that is available to plants and the estimate presented by Smith. The parameter a15 is assumed therefore to equal 0.0016 kilograms of nitrogen per kilogram of manure. All of the nitrogen present in inorganic fertiliser is assumed to be available to growing crops.

5.3.7 Weeds.

In this section the parameters associated with the growth and decay of weeds in crops and the implications of weeds on crop yield are presented. As previously discussed, weeds are explicitly modelled in cereal crops that produce feed grains. These include spring feed barley, spring feed barley that is undersown with pasture, winter feed barley and winter feed wheat. Parameters that relate to the influence of weeds on the rate of combine harvesting and cost of crop drying are presented in Appendix 4.1.

Most of the data in the literature on weed density is presented in units of percentage ground cover or number of weed plants per m^2 (see for example Courtney and Johnson, 1986; Cussans and Moss, 1982; Davies 1988; Davies *et al*, 1990, Jensen, 1985; Orson, 1980; Walker *et al*, 1990; Whiting and Davies, 1990; Wilson, 1986; Wilson *et al*, 1990). Although this data is relatively inexpensive to collect (Whiting *pers. comm.*, 1995) and is useful for the construction of population and economic threshold models (see for example, Cousens 1986; Dent *et al*, 1989; Doyle, 1989; Heitefuss *et al*, 1987; Pannell, 1990; Streibig, 1989; Thornton *et al* 1990), it is of limited value to this study. In the current study the growth of weed biomass is of interest.

There are relatively few studies where the amount of weed dry matter in a growing crop is recorded. However, some studies that do consider weed dry matter are reviewed by Elliott (1980). These include Peters (1978), an unpublished experiment performed in 1980 by the Weed Research Organisation (WRO), and an experiment performed by Cussans (1968). In the study performed by Peters (1978) the difference in dry matter (other than grain) that is produced by clean versus weedy crops of spring barley is recorded. If it is assumed that differences in dry matter between clean and weedy crops can be attributed to weeds, then the magnitude of these differences provide an estimate of the above ground dry weight of weeds. In these experiments, the average of these differences equals 0.7 tonnes per hectare.

With respect to the experiments performed by the WRO, the presence of weeds is measured in crops of winter barley and winter wheat. In the trial involving winter barley, there was a difference in material other than grain of 1.86 tonnes per hectare between a crop where no weed control measures had been applied and one where weeds were controlled. In contrast, there was little difference between the amount of material other than grain, produced by winter wheat, for any of the weed control treatments.

In the trials conducted by Cussans (1968), different levels of couch infestation in crops of spring sown cereals were evaluated. Cussans found differences in the dry weight of material other than grain between the least and most heavily infested crops of approximately 20 and 30 tonnes per hectare. Although Cussans results give an indication of the amount of weed material that can occur in extreme circumstances, it is unlikely that infestations of this order would occur in crops that are subjected to normal levels of husbandry (Whiting *pers. comm.*, 1995).

Rather, the trials performed by Peters (1978) and the experiments performed by the WRO are likely to provide an indication of weed levels that are more typical than those found by Cussans (1968). Although these trials tend to understate the amount of weed material present in a field, the extent of this reduction is not clear. It is assumed, therefore, that the maximum above ground dry weight of weeds is 1.2 tonnes per hectare, which is intermediate to the estimate of 0.7 tonnes per hectare from Peters and 1.86 tonnes per hectare from the winter barley experiments conducted by the WRO.

There are two reasons that the trials conducted by Peters (1978) and the WRO are likely to under estimate the amount of weeds in a crop. The first, is that material other than grain is a measurement of dry matter that passes through a combine harvester. The dry weight of weeds that are below the height of the combines cutting bar are, therefore, excluded from measurement. The second reason is related to the competition between weeds and growing crops. In a weedy crop, the amount of straw that is produced tends to be lower than in a clean crop (Elliott, 1980). As the calculation of the above ground dry matter of weeds assumes that there is no change in the crop material in a field this may introduce errors into the analysis. In the current study it is assumed that these errors are small and that no purpose would be served by adjusting the estimate of above ground weed material to account for these errors.

It is assumed that the potential growth profile of weeds is proportional to the potential growth of the crop in which the weed is growing. Because of the poor quality of data relating to weeds, it is assumed that weed growth does not vary between climates, regions or sowing dates. The potential rate of crop growth that is considered, therefore, is an average of the regions, current climate and earliest sowing date that are represented. The potential growth of weeds in crops that are planted on the second and third sowing dates are assumed to be the same as the first sowing date.

Further assumptions are that in the first month of crop growth the potential growth of weeds is specified by parameter a6; during the remaining months of growth a6 is set to 0, and potential weed growth is defined by parameter a7 (see Equation 5-11). The purpose of this construct is to express the influence of weed control applications, on rates of weed growth, that occur in time periods subsequent to the control measure. It is also assumed that losses of weeds, that are associated with normal processes of death and decay, are the same as the proportion of grass that dies in each period. Parameters a6 and a7 were estimated based on these assumptions (see Table 5-12 and Table 5-13).

Table 5-12. Potential Weed Growth (kg hectare^{-1}) (a6, see Equation 5-11)

Crop	Sowing Date	Commencement of weed growth	a6
Spring Feed Barley	March	April	61
	April	April	61
	May	May	433
Spring Feed Barley (undersown)	March	April	61
	April	April	61
	May	May	433
Winter Feed Barley	September	September	5
	October	October	67
	November	November	94
Winter Feed Wheat	October	November	5
	November	November	5
	December	December	11

Table 5-13. Potential Weed Growth (kg growth kg weeds^{-1}) (a7, see Equation 5-11)

	a7			
	Spring Feed Barley	Spring Feed Barley (undersown)	Winter Feed Barley	Winter Feed Wheat
January	0	0	0.77	2.05
February	0	0	0.96	1.84
March	0	0	1.42	2.12
April	0	0	1.44	2.19
May	6.76	6.76	1.07	1.75
June	1.83	1.83	1.02	1.18
July	0.98	0.98	0.70	0.78
August	0.84	0.84	0	0.83
September	0.80	0.80	0	0.80
October	0	0	12.40	0
November	0	0	1.10	0
December	0	0	0.89	1.77

Weeds reduce crop yields by reducing the pool of nitrogen that is available to crops and by competing for other nutrients and scarce light and moisture (see Section 5.2.3). The competition for nitrogen between weeds and crops is explicitly represented in the model. However, to account for the influence of weeds on the availability of resources that are not expressly modelled, it is necessary to estimate the parameters a4 (see Equation 5-2) that specify changes in yield with changes in weed density.

A series of trials conducted by the Scottish Agricultural Colleges between 1979 and 1988 was reviewed by Davies *et al* (1990) and Davies (1988). In these trials the yield of cereal crops that are subjected to weed control measures at commercially recommended rates are compared with crops that are not treated with herbicides. In spring sown barley, Davies *et al* found a small improvement in yield for crops that were treated with herbicides compared with crops that were untreated. The average yield of weedy crops was 1.7 percent less than crops that were treated with herbicide; a difference of approximately 100 kg per hectare. It is assumed that the losses due to weeds are the same for undersown crops of spring barley. For winter barley and winter wheat the yield of untreated crops were respectively 9.3 percent (or 675 kg per hectare) and 3.5 percent (or 250 kg per hectare) less than the yields of treated crops.

The yield losses that are due to competition for nutrients other than nitrogen and for light and moisture, are assumed to be 50 percent of the estimates from Davies *et al*. The remaining 50 percent of yield losses are attributed to the uptake of nitrogen by weeds. Although attributing yield losses in this way is arbitrary, informal testing of this aspect of the model produced plausible results. The parameter a4 is estimated for the various crops by dividing the yield loss associated with weeds competing for scarce resources other than nitrogen by the sum of the potential quantity of weeds that are present in the crop each month. The estimates of a4 are listed in Table 5-14.

Table 5-14. Yield Loss Associated with Weeds (kg. kg weeds^{-1} month^{-1}) (a4, see Equation 5-2)

Crops	a4
Spring Feed Barley	0.010
Spring Feed Barley (undersown)	0.010
Winter Feed Barley	0.069
Winter Wheat	0.026

5.3.8 Pesticides.

The parameters that relate to pesticides are presented below. A list of the chemicals that are applied to the various crops, and the rates and timings of these applications can be found in Table 5-2. For crops that produce human feedstuffs and pasture and swedes, it is assumed that herbicides are applied at commercially recommended rates. The response of these crops to applications of chemicals are not therefore considered. As discussed in Section 5.2.3, the growth of weeds and response to pesticides is modelled in cereal crops that produce animal feeds.

An assumption of the study is that if herbicides are applied at commercially recommended rates - all weeds present in a field will be destroyed. If the herbicides are applied at less than the maximum rate, a proportional reduction in the quantity of weeds killed is assumed to occur. To estimate the efficacy of individual herbicides, a similar method to that used to estimate the efficacy of other pesticides is employed. It is assumed that in a particular crop and month of chemical application, that the quantity of weeds that are killed by herbicides, per unit of spray cost, is constant where spray cost is the cost per unit of active ingredient. The estimates of a8, that represent the amount of weeds killed per unit of herbicide active ingredient (see Equation 5-7) are presented in Table 5-15.

Table 5-15. Efficacy of Herbicides (kg weeds killed per kg of a.i. of herbicide) (a8, see Equation 5-7)

Crop	Chemical	Month of Application	kg weeds killed per kg of a.i. Sowing Date		
			'1'	'2'	'3'
Spring Feed Barley and undersown Spring Feed Barley	mecoprop & metsulfuron-methyl	May	433.20	433.20	433.20
Winter Feed Barley	linuron & trifluralin	Month of planting	1.33	16.80	23.60
	mecoprop & metsulfuron-methyl	March	179.50	179.50	179.50
Winter Feed Wheat	linuron & trifluralin	Month of planting	0.00	1.25	2.65
	mecoprop & metsulfuron-methyl	March	70.25	70.25	70.25

A number of fungicides and insecticides are represented in the model, also, these can be applied at different times during the growing season[89]. In the absence of suitable experimental data it is necessary to make assumptions regarding the yield increment to be assigned to pesticides of these types and also the temporal distribution of yield increments. With respect to the allocation of yield increments between pesticides, it is assumed that an equal increase in yield occurs for each pound spent on pesticides. Further, the increase in yield is distributed in equal monthly amounts between the time that the pesticide is applied and the next application of the same pesticide. If the pesticide is only applied once or if the application is the last to be applied then it is assumed that the increase in yield is distributed in equal amounts between the month of application and the month of harvest. Another assumption is that the influence of a pesticide on crop yield is the same regardless of the planting date.

It is also necessary to estimate the overall yield increase to be attributed to insecticides and fungicides. With regard to winter wheat, Schofl *et al* (1994) present data that relate to a series of trials that was carried out in the UK between 1990 and 1993. From Schofl *et al*, the average difference in yield between untreated crops and crops that are sprayed 3 times per season is 1.06 tonnes per hectare. In another set of trials, Wale (1994) considers the response of winter wheat to applications of tebuconazole (1 litre per hectare applied at growth stages 32, 39 and 59) at Edinburgh and Aberdeen. In this experiment the yield response to the fungicide is 3.2 and 2.42 tonnes per hectare, respectively. Wale also compared winter wheat responses to fungicides at Aberdeen with responses found at other sites in Britain. At Aberdeen in 1991 and 1992, yield differences between crops that were treated with fungicides were 4.11 and 3.11 tonnes per hectare greater than in untreated crops. In this study, it is assumed that the potential response to fungicides and insecticides in winter wheat crops is 2.5 tonnes per hectare, which is intermediate to the estimates of Schofl *et al* (1994) and Wale (1994).

The yield response to fungicides and insecticides in winter feed barley, is estimated from data presented by Jordan and Stinchcombe (1986). They present data from two sets of trials that relate inputs to the yield and quality of winter barley crops. In trials that were conducted in 1983, the average difference in yield between crops that received fungicide applications and crops that did not was 2.16 tonnes per hectare.

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[89] In the remainder of this section the term pesticides is used when referring to insecticides or fungicides.

This compares to a difference of 1.88 tonnes per hectare for a trial conducted in 1985. In this study, the response to pesticide applications is assumed to be 2.0 tonnes per hectare. With respect to spring feed barley - no suitable data could be found. It is therefore assumed that the pesticide response in spring feed barley is the same as in winter feed barley. The resulting estimates of the yield response to insecticides and fungicides are included in Table 5-16.

Table 5-16. Yield Response to Insecticides and Fungicides. (kg yield per kg of a.i. of pesticide) (a3, see Equation 5-2)

Spring Feed Barley and Spring Feed Barley (undersown)	fenpropimorph (May)	fenpropimorph (June)	pirimicarb (June)	
May	0.976			
June		0.244	0.012	
July		0.244	0.012	
August		0.244	0.012	
September		0.244	0.012	
Winter Feed Barley	tridemorph (November)	fenpropimorph (March)	fenpropimorph (May)	pirimicarb (June)
November	0.064			
December	0.064			
January	0.064			
March	0.064	0.345		
April	0.064	0.345		
May	0.064		0.173	
June	0.064		0.173	0.396
July	0.064		0.173	0.396
August	0.064		0.173	0.396
Winter Feed Wheat	prochloraz (April)	tridemenol, tridemorph & chlormequat (May)	pirimicarb (June)	propiconazole (June)
April	0.112			
May	0.112	0.150		
June	0.112	0.150	0.295	0.303
July	0.112	0.150	0.295	0.303
August	0.112	0.150	0.295	0.303
September	0.112	0.150	0.295	0.303

6. ANIMAL MODELS.

The models described in this chapter are structured to assess the influence of a change in climate on animal systems at farm, regional and national levels. The animal farming systems included in this study are a beef fattening operation, a self replacing ewe flock and a dairying system. The form of these models is significantly influenced by the conventions and assumptions adopted by Topp and Doyle (1994) whose models were used to estimate many of the parameters in the linear programming model. However, there are substantial differences between the approach of Topp and Doyle and that of the current study as LP is considerably less flexible than simulation modelling in terms of the forms of relationships that can be expressed, and the length of time step (a month rather than a daily step) that can reasonably be included.

The principle impact on animal systems of a change in climatic conditions is assumed to operate through variations in the productivity of forage (Topp and Doyle, 1994). In the linear programming model, climatic variables are not explicitly modelled, rather it is assumed that the effects on animal systems of a change in climate are accounted for by specifying changes in the potential productivity of pasture. The absence of climatic variables in the model means that parameters relating to pasture production must be estimated for each climatic change scenario, region and soil type that are considered. In comparison, it is assumed that the physiological responses of animals do not change with climate, so it is only necessary to estimate parameters (given a restricted set of management variables) for a single instance of each of the modelled animal systems.

The following chapter is in three sections. The first provides an overview of the farming systems that are modelled by Topp and Doyle (1994). In the second section, the equations and parameter estimates that describe animal performance are presented. The formulation of the LP model is compared with Topp and Doyle's model and various theoretical considerations are discussed. In the final section the parameter estimates that relate to management variables and the methods by which they are derived are discussed.

6.1 Simulation Models.

The models of Topp and Doyle (1994) include detailed simulation models of grass and grass-clover swards, beef fattening animals, dairy cows and sheep. These models were established in a SOAEFD funded project to analyse the impact of climatic change on Scottish agriculture. The models were therefore developed and validated for Scottish conditions and account for variations in climatic conditions. An assumption of Topp and Doyle's study is that variations in temperature and humidity do not extend beyond the 'comfort zone' of an animal for the climate change scenarios and regions considered. This assumption was adopted as heat stress is unlikely to affect the physiological responses of animals in Scotland, while farmers are able to mitigate the effects of low temperature through actions such as housing animals. Further, it is unlikely that changes in humidity will alter animal performance (Doyle *pers. comm.*, 1995).

The background and objectives associated with these models make them particularly well suited to provide data to this study. Topp and Doyle adopt a daily time step in their models and the equations that predict changes in the physiological status of the different types of animal tend to be similar in each of the models. In the dairy herd model, animals are assumed to calve in spring, and are rotationally grazed during the summer on 12 equal sized fields. Animal intake is comprised of a fixed amount of concentrates fed each day and ingested forage from either grass or grass-clover swards. The model accounts for the conservation of hay and silage but feeding of conserved forage was not represented. The model could, however, be readily modified to allow for the feeding of hay and silage (Topp *pers. comm.*, 1995).

Animals are assumed to calve indoors, and when sufficient forage is available (measured in terms of average pasture dry matter per hectare) animals are turned onto pasture. The date of yarding in autumn is similarly determined by monitoring when average pasture availability falls below a pre-determined limit. The herd is represented as an 'average cow', and it is assumed that the herd maintains a constant age structure from year to year with 25 percent of animals as first year heifers, 25 percent as second year heifers and the remainder of the herd as mature animals of mixed age. The presence and disposal of calves and culling of aged or low producing cows and their subsequent replacement are not considered.

With regard to the beef model, Topp and Doyle (1994) consider an 18 month steer fattening system involving the purchase of autumn born calves. The calves are housed over winter, and are turned onto pasture in spring. In the following winter, the yearling animals are housed and finished indoors before being sold for slaughter. As in the dairy cow model, the date of turn-out and subsequent yarding occurs when the amount of herbage increases above a specified limit in spring and declines below an autumn limit. The model of beef animals is constructed to represent an average animal, and the rule base used to control rotational grazing and closure and cutting of fields for hay and silage is the same as that used in the dairy model. As the primary output of the beef model relates to predictions of variations in liveweight, weight changes were modelled in more detail than in the dairy or sheep models and include state variables that represent changes in the level of DNA and fat and protein accretion. This compares with the dairy and sheep models where liveweight is represented as a single variable.

In the sheep model, lambing is assumed to occur in spring and animals are turned onto pasture when sufficient forage is available. Topp and Doyle treat the date of tupping as a constant, so that lambing occurs on March 15. The model is structured to represent an instance of an average ewe, and an instance of an average number of suckling lambs. An assumption of the model is that the mature ewe is the average age of the flock, and that the age of the animal does not change between years. Lambs are modelled as the average of a ewe lamb and a castrate male lamb. Lambing percentage is treated as an exogenous variable, and lamb birth weight is assumed to vary with the sires mature weight and the weight of the dam during gestation. Weaning of lambs, is not discussed by Topp and Doyle. Meat production is calculated as the total weight of lambs at the time of yarding, and there is no allowance for lambs to be sold earlier in the season. Cash income from wool production typically only accounts for 3 to 4 percent of a sheep's gross margin (SAC, 1994), and thus is not considered in the simulation model.

6.2 Linear Programming Models.

The LP models presented below were constructed after a review of the literature and are strongly influenced by Topp and Doyle's (1994) models which were developed concurrently with the models included in this study. The LP model of the beef fattening operation involves purchasing 6 month old steers in winter, which are held on the farm for 12 months before being sold. This corresponds to the time series data that were provided to this study, but differs slightly from the system reported by Topp and Doyle (1994). It is assumed that animals are purchased on a specified day, but provision is made for animals to be sold over a range of different dates. The structure of the dairy and sheep farming systems included in the LP models is similar to the models of Topp and Doyle. The dairy herd and ewe flock are modelled as an average animal, that produces off-spring on the date specified by Topp and Doyle.

The LP model selects the animals diet from a range of locally purchased and farm produced feed-stuffs that result in an optimal sequence of weight gains. The number of animals that are carried on the farm is subject to a limit on housing, labour and working capital. The various feed-stuffs included in the model are specified in terms of digestibility and energy content (see Table 6-1). A potential energy intake limit, and also a limit on the ability to consume indigestible dry matter, are specified as functions of the time of year and liveweight. Animal growth is calculated as a function of achieved energy intake less requirements for maintenance and reproductive requirements.

In the remainder of this section, the structure of the LP models are presented and issues associated with differences between the LP models and the models of Topp and Doyle (1994) are discussed. The data that is utilised in this study includes information about the structural assumptions and parameter estimates adopted by Topp and Doyle. Also, time series data were established for each combination of the factors: three climates, four regions, four soil types, two pasture types, three stocking rates, and three animal systems. The resulting 864 scenarios, each with a 10 year duration, provide a record of changes in the status of pasture and animal variables through simulated time. This data was used to establish many of the parameters in the LP model, and was particularly useful where the LP model adopts different assumptions relating to physiological responses than do Topp and Doyle or the differing temporal and spatial scales of the two studies meant that it was not possible to establish a direct correspondence between the models.

Table 6-1 Metabolisable Energy Content, Digestibility and Price of Feeds[90].

Feedstuff	Metabolisable Energy Content (MJME kg DM^{-1})	Digestibility (fraction)	Price (£. tonne DM^{-1})[91]
1: Maize	14.2	0.87	150
2: Wheat Bran	10.1	0.60	100
3: Soya Bean Meal	12.3	0.78	170
4: Linseed Meal	11.9	0.74	140
5: Fish Meal	11.1	0.68	320
6: Oilseed Rape	21.0	0.80	250
7: Feed Barley	13.7	0.86	93
8: Feed Wheat	14.0	0.87	100
9: Feed Potatoes	12.5	0.78	n.a.
10: Hay	9.0	0.60	64
11: Silage	9.3	0.60	n.a.
12: Swedes	11.9	0.76	n.a.
13: Straw	6.5	0.57	26

6.2.1 Grazing and Conservation Management.

There are a number of differences between the management component of the LP model and the approach of Topp and Doyle (1994). One reason for this relates to the method used to control the models. The simulation models adopt a rule based approach to model grazing and conservation decisions while the LP models are an inherently optimising technique. Another difference relates to the level of spatial resolution that is considered in the respective approaches. Topp and Doyle (1994) model the farm as having 12 equal sized fields containing either grass or grass-clover swards. Their model includes a rule base that controls the closure and cutting of fields for hay and silage. Grazing rules, based on the availability of pasture, specify when animals are turned out to graze in the spring and also when animals are returned to be housed in the autumn. Other grazing rules ensure that animals are moved from a field when the pasture cover declines below a specified limit. The field that animals are moved into is selected as having the highest dry matter cover of the fields that are available for grazing. If feed shortages develop, fields that are closed for conservation, can be made available for grazing.

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[90] Source: Ministry of Agriculture, Fisheries.and Food (1977) Energy Allowances and Feeding Systems for Ruminants. Technical Bulletin 33. HMSO (London).

[91] Source: SAC (1995) *Monthly Economic Reports*. Scottish Agricultural College.

Topp and Doyle (1994), relate grazing and conservation decisions to individual fields, but the unit of land considered in the farm LP models is the area of a soil type planted to a class of pasture. The LP model includes six classes of pasture where the pasture class is defined in terms of whether the sward is grass or grass-clover, and whether the pasture is conserved for silage or hay, or can only be grazed. Further, the pasture classes are represented on each of the four soil types that are included in the model. The pasture classes were defined to allow pasture conservation to be better considered. However, the method of classifying pasture classes is not suitable for modelling rotational grazing particularly when the length of time step that is used in the model (a month) is considered. Rather, the LP model reflects a set stocking system that allows animals to disperse between the different soil and pasture classes on the farm.

The date that animals are turned onto pasture after winter, and the date that animals are returned to be housed at the end of the grazing season is determined using data from the simulated series produced by Topp and Doyle (1994). In the LP model, the dates at which turning out and turning in occur are calculated for each animal system, region, soil type and climatic scenario. The method of determining the dates of these events and also the timing of conservation operations for hay and silage is discussed further in Section 6.3.

6.2.2 Animal Reconciliation.

Animals are categorised in terms of weight, using a modification of the segmentation method of Duloy and Norton (1975). This allowed the physiological responses that vary with liveweight to be approximated with functions that are pieci-linear in form. These include: inter-period transfers of animal weight, metabolic energy requirements, physical limits to the intake of indigestible dry matter, and sale prices that can vary with the market grade that an animal achieves. The animal reconciliation acts by requiring animals to be placed in appropriate weight categories. An example of this segmentation procedure being applied to an agricultural problem, can be found in Morrison *et al* (1986) who describe responses in crop yield to variations in soil nitrogen. For situations where the selected response is convex, with respect to the objective function, the method provides an efficient method for describing non-linear relationships.

Figure 6-1. Animal Sub-matrix[92].

	Animal Intake				Animal Weight		Animal Purchases	Animal Sales		Feed Intake
	j=1,k=1	j=1,k=2	j=2,k=1	j=2,k=2	j=1	j=2		j=1	j=2	
Animal Weight	-A[93] -A -A	-A[93] -A -A	-A[93] -A -A	-A[93] -A -A	A [94] -A A -A A	A [94] -A A -A A	-A [95] -A -A	A [96] A A	A [96] A A	
Animal Number					1 [97] -A 1 -A 1	1 [97] -A 1 -A 1	-1 [95] -1 -1	1 [96] 1 1	1 [96] 1 1	
Permit MEI j=1	1 [98] 1 1	1 [98] 1 1			-A [99] -A -A					
Permit MEI j=2			1 [98] 1 1	1 [98] 1 1		-A [99] -A -A				
Permit MEI j=1,k=1	1 [100] 1 1				-A [101] -A -A					
Permit MEI j=2,k=1			1 [100] 1 1			-A [101] -A -A				
Energy Intake	1 [102] 1 1	1 [102] 1 1	1 [102] 1 1	1 [102] 1 1						-A [103] -A -A
Permit IDOMI					A [104] A A	A [104] A A				-A [105] -A -A

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[92] 'A' refers to non-zero coefficients that are not equal to unity.

[93] Liveweight gain that is due to intake is classified by liveweight category (j=1..4) and level of intake (k=1..2) (see Equation 6-3).

[94] Interperiod transfer of animal liveweight is classified by liveweight category (j=1..4) (see Equation 6-3).

[95] The purchase of animals supplies animal liveweight and animal numbers (see Equations 6-1 and 6-2).

[96] Animal sales reduce animal liveweight and animal numbers and are classified by liveweight category (j=1..4) (see Equations 6-1 and 6-2).

[97] Interperiod transfer of animal numbers is classified by liveweight category (j=1..4) (see Equation 6-2).

[98] Achieved intake is classified by liveweight category (j=1..4) and level of intake (k=1..2) (see Equation 6-3).

[99] Potential metabolisable energy intake by animals (see PMEI in Equation 6-6).

[100] Limit on achieved intake by animals that is associated with pregnancy and maintenance (see $MEI_{t,j,1}$ in Equation 6-4).

[101] Limit on potential metabolisable energy intake by animals that is associated with pregnancy and maintenance (see $MEI_{t,j,1}$ in Equation 6-4).

[102] Actual intake of metabolisable energy that is associated with ingested feeds (see Equation 6-7).

[103] Metabolisable energy content of ingested feed (see Equation 6-7).

[104] Ruminal capacity of animals (see Equation 6-8).

[105] Indigestible organic dry matter content of ingested feed (see Equation 6-8).

In the LP model, four weight classes are defined, and the year is comprised of 12 monthly periods. For reasons of clarity, two weight classes and 3 time periods are presented in Figure 6-1, which depicts the structure of an animal sub-matrix. In the diagram, "A" refers to variables that do not equal zero or unity. The weight classes refer to increasingly heavy animals, so that processes that vary non-linearly with liveweight are calculated directly as a function of the respective animal weight. The estimation of these weight classes is accomplished by running the animal farming models of Topp and Doyle (1994) for each possible combination of management, climate and regional scenario, and determining the minimum and maximum animal weights that occur for each of the modelled animal classes and time periods. Intermediate weight classes were derived by interpolating between these bounds (see Table 6-2 and Figure 6-2).

The principle equations describing the reconciliation of animal numbers and liveweights are as follows:

$$LW_{t,j} = N_{t-1,j}\,(LW_{t-1,j} + \Delta LW_{t,j}) + N_{Pt,j}\,LW_{t,j} - N_{St,j}\,LW_{t,j} \qquad (6\text{-}1)$$

$$N_{t,j} = N_{t-1,j} + N_{Pt,j} - N_{St,j} \qquad (6\text{-}2)$$

where N is the number of animals; j is the liveweight category of the animal; t is the modelled time period; LW is animal liveweight (kg head^{-1}); ΔLW is change in liveweight (kg head^{-1}). N_P and N_S are the number of animals that are purchased and sold.

Table 6-2. Liveweight Classes (kg. head^{-1}).

Beef Animals.

	Class 1	Class 2	Class 3	Class 4
January	167.8	167.8	167.8	167.8
February	181.5	189.35	197.2	205.0
March	195.2	210.9	226.6	242.3
April	208.9	229.1	249.4	269.7
May	222.6	247.3	272.0	296.8
June	236.3	265.2	294.2	323.2
July	250.0	282.4	314.9	347.4
August	261.3	297.6	333.9	370.3
September	272.6	312.6	352.6	392.6
October	283.9	329.1	374.3	419.6
November	295.2	341.8	388.4	435.1
December	306.5	354.5	402.5	450.6

Dairy Animals.

	Class 1	Class 2	Class 3	Class 4
January	585.0	585.0	585.0	585.0
February	560.4	568.6	576.8	585.0
March	535.8	552.2	568.6	585.0
April	511.2	535.8	560.4	585.0
May	486.7	519.4	552.2	585.0
June	478.0	513.6	549.3	585.0
July	486.7	519.4	552.2	585.0
August	499.2	527.8	556.4	585.0
September	520.6	542.1	563.5	585.0
October	542.1	556.4	570.7	585.0
November	563.5	570.7	577.8	585.0
December	585.0	585.0	585.0	585.0

Sheep.

	Class 1	Class 2	Class 3	Class 4
January	64.6	64.6	64.6	64.6
February	61.8	62.7	63.7	64.6
March	59.0	60.9	62.7	64.6
April	56.2	59.0	61.8	64.6
May	53.3	57.1	60.9	64.6
June	50.5	55.2	59.9	64.6
July	53.8	57.4	61.0	64.6
August	55.6	58.6	61.6	64.6
September	57.9	60.1	62.4	64.6
October	60.1	61.6	63.1	64.6
November	62.4	63.1	63.9	64.6
December	64.6	64.6	64.6	64.6

Lambs.

	Class 1	Class 2	Class 3	Class 4
March	5.2	6.3	7.4	8.6
April	7.3	11.0	14.7	18.5
May	12.2	17.8	23.5	29.2
June	21.5	27.1	32.6	38.1
July	30.9	35.8	40.6	45.5
August	34.6	40.2	45.7	51.3
September	38.3	44.3	50.2	56.2
October	42.0	47.9	53.7	59.6
November	45.7	51.5	57.2	63.0
December	49.4	55.1	60.7	66.3

Change in liveweight is calculated by Topp and Doyle (1994) as the net change in weight between adjacent days. To estimate weight changes in the LP models, that are comparable to the estimates of Topp and Doyle, ΔLW is calculated as follows.

$$\Delta LW_{t,j} = \frac{\sum_{k=1}^{2} kf_k \, a25_{t,j,k} \, MEI_{t-1,j,k}}{a26_{t,j}} - LWL_{t,j} \qquad (6\text{-}3)$$

where kf is the efficiency of utilisation of metabolisable energy for liveweight growth; a25 is the proportion of metabolisable energy intake allocated to animal growth (see Table 6-8 and Table 6-9); a26 is the energy content of liveweight (MJME kg^{-1}, see Table 6-4); MEI is the energy intake that an animal achieves (MJME $head^{-1}$), where energy intake is classified as being either less than ($k = 1$) or greater than maintenance plus pregnancy requirements ($k = 2$); LWL is the loss in liveweight that would occur if the animal is subjected to a zero level of feeding (kg $head^{-1}$) and are estimated from Topp and Doyle's time series data (see Table 6-3).

MEI is classified according to whether ingested energy is less than or greater than the amount required to maintain an animals weight for two reasons. The first is that the efficiency of utilisation of metabolisable energy for liveweight growth (kf), is different during periods of weight loss than when animals are gaining weight. For each of the models kf_1 is assumed to equal 1 and kf_2 equals 0.32 (ARC, 1980). The second reason for segmenting metabolisable intake is related to variations in the relative ability of different physiological processes to obtain energy from the pool of metabolisable energy depending on the level of MEI (Baldwin and Black, 1979). A method that was used by Baldwin and Black to model this source of variation was to specify Michaelis-Menten equations that describe the amount of energy used by each process as a convex function of the amount of metabolisable energy that is available for allocation. The classification of MEI and the specification of kf and a25 for each k, allows responses of this kind to be approximated in the model. $MEI_{t,j,1}$ is estimated as follows:

$$MEI_{t,j,1} = Emaint_{t,j} + Epreg_{t} \qquad (6\text{-}4)$$

Table 6-3. Inter-period Liveweight Loss (kg head^{-1}) (LWL, see Equation 6-3)

Beef.

	Class 1	Class 2	Class 3	Class 4
January	91.5	91.5	91.5	91.5
February	94.3	95.9	97.3	98.7
March	96.9	99.7	102.1	104.3
April	99.3	102.5	105.3	107.7
May	101.5	105.0	108.0	110.6
June	103.5	107.2	110.3	113.0
July	105.3	109.1	112.3	114.9
August	106.7	110.7	113.9	116.5
September	108.1	112.1	115.3	117.9
October	109.3	113.5	116.7	119.3
November	110.4	114.5	117.6	120.1
December	111.5	115.4	118.4	120.7

Dairy

	Class 1	Class 2	Class 3	Class 4
January	152.1	152.1	152.1	152.1
February	173.1	172.8	172.6	172.3
March	210.9	209.7	208.5	207.3
April	123.0	123.7	124.3	124.8
May	122.5	123.6	124.4	125.2
June	122.5	123.7	124.6	125.4
July	123.3	124.3	125.1	125.8
August	124.5	125.3	126.0	126.6
September	126.5	127.0	127.5	127.9
October	129.3	129.6	129.9	130.1
November	133.7	133.8	133.8	133.9
December	140.6	140.6	140.6	140.6

Sheep.

	Class 1	Class 2	Class 3	Class 4
January	22.7	22.7	22.7	22.7
February	27.0	27.2	26.6	26.8
March	18.7	18.5	18.4	18.3
April	18.6	18.7	18.2	18.3
May	18.5	18.8	18.5	18.3
June	19.0	18.3	18.3	18.3
July	18.6	18.3	18.6	18.3
August	18.4	18.6	18.2	18.3
September	18.4	18.4	18.3	18.3
October	18.5	18.3	18.6	18.4
November	18.8	19.0	18.6	18.7
December	19.9	19.9	19.9	19.9

Lambs.

	Class 1	Class 2	Class 3	Class 4
March	9.2	10.7	11.7	12.3
April	11.5	14.1	16.5	17.4
May	15.2	17.0	17.7	18.9
June	17.5	18.7	18.7	19.3
July	18.8	19.2	18.7	18.8
August	18.7	19.2	18.9	18.5
September	18.6	19.1	18.9	18.6
October	19.1	18.9	18.6	18.3
November	18.9	18.6	18.3	18.5
December	18.6	18.9	18.5	18.1

Table 6-4. Energy Content of Liveweight (MJME. kg^{-1}). (a26, see Equation 6-3)

Beef.

	Class 1	Class 2	Class 3	Class 4
January	8.4	8.4	8.4	8.4
February	8.7	8.8	9.0	9.1
March	8.9	9.2	9.5	9.8
April	9.2	9.5	9.9	10.2
May	9.4	9.8	10.3	10.7
June	9.7	10.2	10.7	11.2
July	9.9	10.5	11.0	11.6
August	10.1	10.7	11.4	12.0
September	10.3	11.0	11.7	12.4
October	10.5	11.3	12.1	12.9
November	10.7	11.5	12.3	13.2
December	10.9	11.7	12.6	13.4

Dairy.

	Class 1	Class 2	Class 3	Class 4
January	15.8	15.8	15.8	15.8
February	15.4	15.5	15.7	15.8
March	15.0	15.2	15.5	15.8
April	14.5	15.0	15.4	15.8
May	14.1	14.7	15.2	15.8
June	13.9	14.6	15.2	15.8
July	14.1	14.7	15.2	15.8
August	14.3	14.8	15.3	15.8
September	14.7	15.1	15.4	15.8
October	15.1	15.3	15.6	15.8
November	15.4	15.6	15.7	15.8
December	15.8	15.8	15.8	15.8

Sheep.

	Class 1	Class 2	Class 3	Class 4
January	18.9	18.9	18.9	18.9
February	18.4	18.4	18.9	18.9
March	17.3	17.8	18.4	18.9
April	16.8	17.3	18.4	18.9
May	16.2	16.8	17.8	18.9
June	15.2	16.8	17.8	18.9
July	16.2	17.3	17.8	18.9
August	16.8	17.3	18.4	18.9
September	17.3	17.8	18.4	18.9
October	17.8	18.4	18.4	18.9
November	18.4	18.4	18.9	18.9
December	18.9	18.9	18.9	18.9

Lambs.

	Class 1	Class 2	Class 3	Class 4
March	5.6	5.6	5.8	6.1
April	5.8	6.5	6.9	7.7
May	6.5	7.7	9.1	10.1
June	8.7	9.6	11.1	12.1
July	10.6	11.6	13.1	14.1
August	11.6	12.6	14.1	15.7
September	12.6	13.6	15.2	16.8
October	13.1	14.7	16.2	17.8
November	14.1	15.7	17.3	18.4
December	15.2	16.2	17.8	19.5

where Emaint is the metabolisable energy required to maintain an animal (MJME), and Epreg is the metabolisable energy requirement of gestation (MJME). Emaint and Epreg are assumed to be nutritionally non-responsive requirements and are estimated from the time series data of Topp and Doyle (1994) (see Table 6-5).

The liveweight loss of a fasted animal (LWL) is calculated as a function of the energy content of liveweight, and the requirements for maintenance and pregnancy.

$$\mathrm{LWL}_{t,j} = \frac{\mathrm{MEI}_{t,j,1}}{a26_{t,j}} \qquad (6\text{-}5)$$

A further point relating to the segmentation of animal weights, is the increasing proportion of weight gain attributable to fat deposition, that occurs as animals mature and become heavier (Searle and Griffiths,1976; ARC 1980). As fat has a high energy content relative to other body constituents, the metabolisable energy intake that is required to achieve a given gain in an animals weight will also tend to increase as the animal becomes heavier. The specification of a26 for animals of differing weights enables the variable contribution of MEI to animal growth to be included using a pieci-linear function.

Equations 6-4 and 6-5 are sufficient to account for variations in the numbers and liveweights of animals where the animals are relatively homogenous in terms of age, sex and weight. For beef fattening systems, it is assumed that the annual pattern of purchasing and selling ensures a reasonable degree of consistency amongst the animals present on the farm. This assumption is consistent with Topp and Doyle (1994) who model a single class of beef animals.

With respect to 'dairy' farms, the assumption of homogeneity is more tenuous as calves are produced each year and at any one time the dairy herd will be comprised of animals with differing ages. For simplicity, assumptions relating to the age composition of the herd follow those of Topp and Doyle (1994). The herd of lactating cows is represented as a multiple of an average dairy cow, and it is assumed that 25 percent of the animals are replaced annually, so that the herd maintains a

Table 6-5. Metabolisable Energy Required for Maintenance and Pregnancy. (MJME. month^{-1})

Beef.

	Class 1	Class 2	Class 3	Class 4
January	776	776	776	776
February	823	850	876	902
March	870	922	973	1023
April	915	981	1045	1108
May	960	1039	1116	1191
June	1004	1095	1183	1270
July	1047	1148	1245	1340
August	1082	1194	1301	1406
September	1117	1238	1355	1469
October	1152	1287	1418	1544
November	1186	1324	1458	1587
December	1220	1361	1497	1629

Dairy.

	Class 1	Class 2	Class 3	Class 4
January	2415	2415	2415	2415
February	2672	2693	2714	2735
March	3164	3206	3248	3290
April	1791	1855	1919	1982
May	1731	1818	1903	1987
June	1712	1807	1899	1991
July	1742	1829	1914	1997
August	1787	1862	1936	2009
September	1864	1919	1975	2029
October	1955	1991	2028	2065
November	2071	2089	2108	2126
December	2232	2232	2232	2232

Sheep.

	Class 1	Class 2	Class 3	Class 4
January	430	430	430	430
February	498	501	505	509
March	324	332	340	347
April	313	324	336	347
May	301	316	332	347
June	289	309	328	347
July	303	318	333	347
August	310	323	335	347
September	320	329	338	347
October	331	337	343	349
November	346	349	352	355
December	377	377	377	377

Lambs.

	Class 1	Class 2	Class 3	Class 4
March	52	61	69	76
April	67	92	115	136
May	99	132	163	191
June	152	181	208	234
July	200	223	245	267
August	217	243	268	292
September	235	261	287	313
October	251	277	302	327
November	268	293	317	341
December	284	308	331	354

constant age structure from year to year. In the current model, calves are not explicitly modelled, rather all calves are assumed to be sold and only the costs, revenues and feed requirements associated with calves are included in the model. A further assumption is that variations in reproductive performance, arising either as a direct or indirect response to changes in climatic conditions are minimal, so that calving percentages are treated as constant

As in Topp and Doyle's (1994) model, the feed intake and numbers and weights of ewes and lambs are explicitly modelled. Both the ewe and lamb models are similar in structure to that presented in Figure 6-1. Linkages between the respective sub-matrices that represent the birth of lambs and transfer of replacements from the lamb group to the mature ewe class are specified. In the LP model, it is assumed that the lambing percentage corresponds to the value specified by Topp and Doyle. With regard to the age structure of the flock similar assumptions to the dairy model are used. The age composition of the flock is assumed to be constant and a fixed proportion of the mature ewe flock is culled each year and replaced with lambs born in the preceding year. Lambs that are not retained as replacements are sold either as stores or for slaughter.

6.2.3 Animal Intake.

Animal intake is a complex process involving dynamic interactions between animal and plant characteristics, and the environment. (Bircham and Sheath, 1986; Bruce et al, 1984; Bywater, 1984; Conrad *et al*, 1964; Poppi *et al*, 1987). The complexity of the processes that are involved make it difficult to predict animal intake accurately, however, the success of modelling a forage grazing system is critically dependent on achieving satisfactory estimates of intake, as livestock performance is principally dictated by nutritional status (Blaxter *et al*, 1956). In this study, it is assumed that the intake of dry matter by animals is regulated by three factors: (1) physiological requirements, (2) physical transmission of ingested feed through the gut, and (3) the ability of an animal to graze swards at low levels of pasture cover. The actual amount of intake that is achieved is assumed to be the minimum of these factors. The feeds available to animals are specified in terms of energy content and digestibility, and animal growth is assumed to be a function of energy intake (ARC, 1976 and 1980; MAF *et al*, 1984).

6.2.3.1 Physiological Limit.

The physiological requirements of an animal (PMEI, MJME head^{-1}) are assumed to be comprised of the requirements for maintenance, pregnancy, lactation and growth in liveweight (ARC,1980), and correspond to the summation of $MEI_{j,1,t}$ and $MEI_{j,2,t}$. PMEI is estimated from the time series data provided by Topp and Doyle's (1994) models. In situations where feed digestibility and availability do not limit the intake of a mature animal, animals will consume at a level that will maintain body condition over a relatively long time period (Bines *et al*, 1969). Bines (1971) suggested that long term regulation of food intake involves physiological mechanisms whereby animals balance energy intake with expenditure.

The amount of energy required for maintenance varies with metabolic body weight, animal age, grazing conditions, feed quality and level of production (Hulme *et al*, 1986; Wallach *et al*, 1984). In the current study, the use of linear programming tended to restrict the formulation to a relatively simple functional form. It is assumed that maintenance can be modelled as a function of liveweight and time of year and is estimated from predictions generated by the models presented by Topp and Doyle (1994) (see Table 6-6). Other factors that influence maintenance and which are addressed by Topp and Doyle (such as age and level of production), are implicit in the derived estimates.

6.2.3.2 Physical Limit.

At low levels of feed digestibility intake is restricted by a physical limit to the amount of undigested material that can pass through the gut (Conrad *et al*, 1964). Bines (1971) considered the limit in physical capacity to be related to ruminal size, rate of chemical and physical breakdown of food in the rumen, and rate of transmission of undigested food residues. Rumen capacity is principally determined by the size of the abdominal cavity, which in turn, is a function of animal liveweight (Grovum, 1979). It has also been suggested that advanced pregnancy and extensive fat deposition within the abdomen reduce ruminal capacity, but evidence supporting this hypothesis is inconclusive (Bines, 1971).

Although some debate exists between researchers regarding the mechanisms and site that control the rate of passage of undigested feed residues through an animals alimentary tract (Grovum and Phillips, 1978), Conrad *et al* (1964) found empirically, in animals that are not pregnant or lactating, that faecal dry matter is voided as a relatively constant function of liveweight. It is assumed here that it is sufficient to model the capacity of an animal to ingest indigestible dry matter as a function of animal liveweight and reproductive requirements.

The equations in the LP model that relate intake to the physical and physiological limits of an animal are as follows:

$$N_{t,j}\,PMEI_{t,j} \geq \sum_{k=1}^{2} MEI_{t,j,k} \tag{6-6}$$

$$\sum_{j=1}^{4}\ \sum_{k=1}^{2} MEI_{t,j,k} \geq \sum_{p=1}^{n} a27_{t,p}\,I_{t,p} \tag{6-7}$$

$$a28_{t,j}\,N_{t,j}\,LW_{t,j} \geq \sum_{p=1}^{n} a29_{t,p}\,I_{t,p} \tag{6-8}$$

The potential energy intake of the animal (PMEI, MJME head^{-1}) is estimated from the time series of Topp and Doyle (1994) (see Table 6-6 and Figure 6-2); a27 is the metabolisable energy content of a feed (MJME kg DM^{-1}); p is the type of feed, and includes pasture and conserved and purchased feeds; n is the number of feeds considered; I is actual intake of a feed (kg DM); a28 is the amount of indigestible feed that animals of different weights can ingest (kg indigestible organic DM. kg LW^{-1}.head^{-1}) (see Table 6-7); and a29 is the indigestible organic dry matter content of a feed (kg indigestible organic DM. kg DM^{-1}).

Figure 6-2. Animal Model Parameters.

Animal Liveweight Categories (kg / head) (see Equation 6-1)

Potential Metabolisable Energy Intake. (MJME / head) (PMEI, see Equation 6-6)

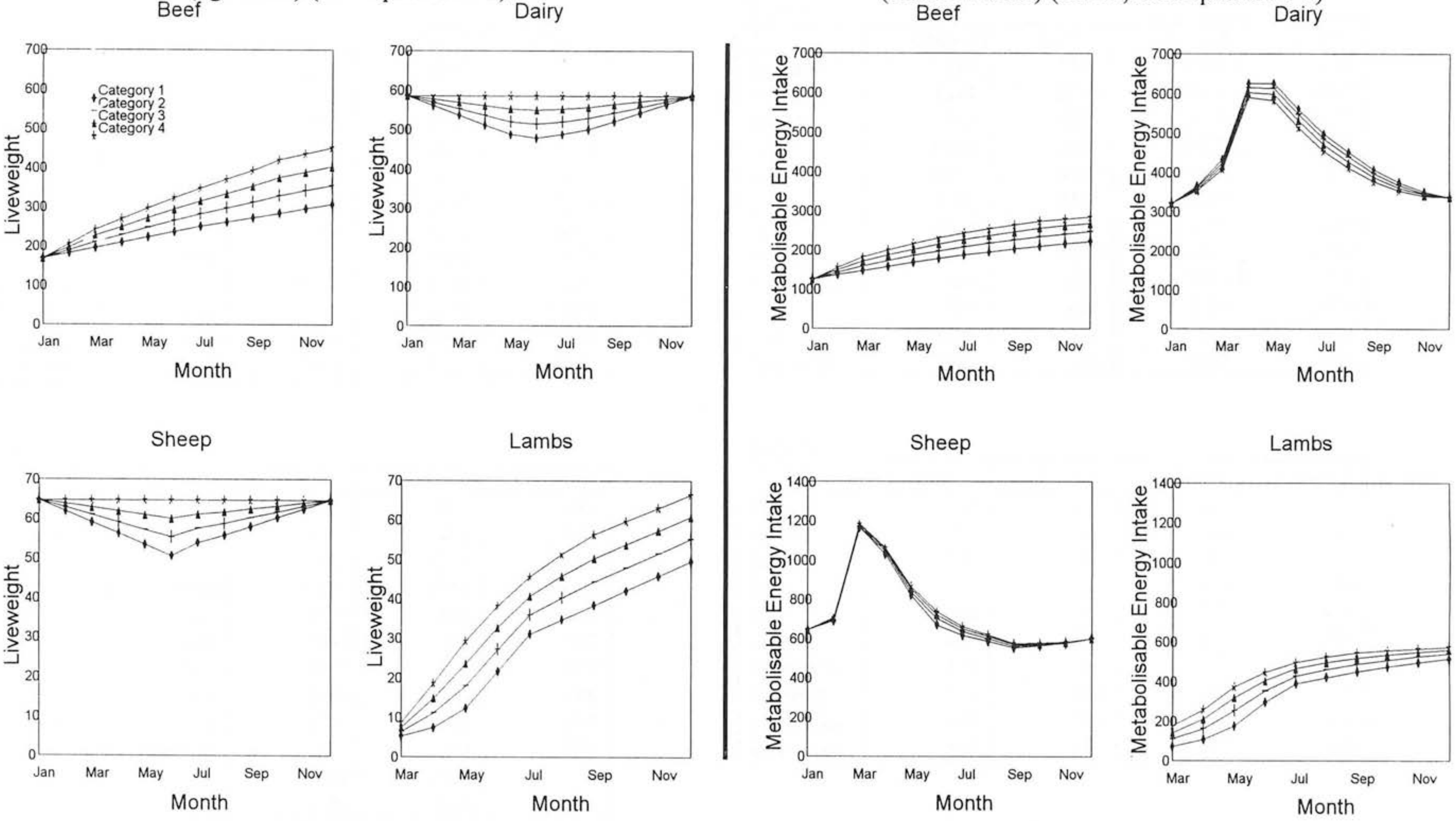


Table 6-6. Potential Metabolisable Energy Intake (MJME head^{-1}) (PMEI, see Equation 6-6)

Beef Animals.

	Class 1	Class 2	Class 3	Class 4
January	1242	1242	1242	1242
February	1356	1420	1482	1543
March	1466	1587	1703	1814
April	1572	1722	1863	1996
May	1674	1849	2011	2161
June	1772	1968	2146	2308
July	1867	2075	2263	2431
August	1942	2166	2364	2538
September	2014	2251	2456	2633
October	2084	2339	2556	2737
November	2152	2404	2616	2791
December	2217	2466	2673	2840

Dairy

	Class 1	Class 2	Class 3	Class 4
January	3197	3197	3197	3197
February	3644	3603	3561	3517
March	4315	4239	4158	4072
April	6239	6134	6018	5891
May	6247	6120	5972	5806
June	5594	5461	5303	5123
July	4962	4835	4687	4520
August	4494	4377	4245	4099
September	4061	3966	3863	3752
October	3734	3666	3595	3520
November	3495	3459	3422	3384
December	3359	3359	3359	3359

Sheep

	Class 1	Class 2	Class 3	Class 4
January	643	643	643	643
February	689	693	701	705
March	1162	1170	1176	1182
April	1028	1041	1052	1060
May	820	837	854	866
June	668	700	720	735
July	615	635	648	659
August	584	597	610	618
September	551	560	568	574
October	561	567	571	575
November	575	576	580	581
December	599	599	599	599

Lambs

	Class 1	Class 2	Class 3	Class 4
March	70	108	140	173
April	105	161	209	257
May	174	251	317	372
June	295	351	403	444
July	388	427	463	493
August	419	459	494	522
September	448	485	517	542
October	471	505	533	554
November	494	523	546	563
December	513	537	557	571

Table 6-7. Physical limit to Intake (kg IDOM. kg LW^{-1}) (a28, see Equation 6-8)

Beef .

	Class 1	Class 2	Class 3	Class 4
January	0.262	0.262	0.262	0.262
February	0.262	0.262	0.262	0.262
March	0.262	0.262	0.262	0.262
April	0.262	0.262	0.262	0.262
May	0.262	0.262	0.263	0.262
June	0.262	0.262	0.262	0.262
July	0.262	0.262	0.262	0.262
August	0.262	0.262	0.262	0.262
September	0.262	0.262	0.262	0.262
October	0.262	0.262	0.262	0.262
November	0.262	0.262	0.262	0.262
December	0.262	0.262	0.262	0.262

Dairy.

	Class 1	Class 2	Class 3	Class 4
January	0.262	0.262	0.262	0.262
February	0.262	0.262	0.262	0.262
March	0.262	0.262	0.262	0.262
April	0.275	0.275	0.275	0.275
May	0.287	0.287	0.288	0.288
June	0.300	0.300	0.300	0.300
July	0.313	0.313	0.313	0.313
August	0.325	0.325	0.325	0.325
September	0.313	0.313	0.313	0.313
October	0.300	0.300	0.300	0.300
November	0.287	0.288	0.287	0.288
December	0.275	0.275	0.275	0.275

Sheep.

	Class 1	Class 2	Class 3	Class 4
January	0.305	0.305	0.305	0.305
February	0.304	0.305	0.305	0.305
March	0.319	0.319	0.319	0.319
April	0.333	0.334	0.333	0.334
May	0.349	0.349	0.348	0.348
June	0.362	0.362	0.364	0.364
July	0.377	0.378	0.377	0.378
August	0.363	0.363	0.364	0.364
September	0.349	0.348	0.348	0.348
October	0.334	0.334	0.334	0.334
November	0.319	0.319	0.319	0.319
December	0.305	0.305	0.305	0.305

Lambs.

	Class 1	Class 2	Class 3	Class 4
March	0.288	0.349	0.405	0.442
April	0.301	0.300	0.306	0.303
May	0.303	0.303	0.302	0.305
June	0.302	0.303	0.304	0.304
July	0.304	0.304	0.305	0.305
August	0.303	0.303	0.304	0.304
September	0.305	0.305	0.305	0.304
October	0.305	0.305	0.305	0.304
November	0.304	0.305	0.304	0.305
December	0.304	0.305	0.305	0.305

A number of researchers have observed a delay between an increase in energy requirements associated with pregnancy and lactation and a corresponding increase in appetite and ability to ingest feed (Arnold and Dudzinski, 1967; Foot and Russell, 1979; Monteiro, 1972; Purser and Moir, 1966; Tulloh, 1966). Bywater (1984) suggests that adjustments in rumen capacity in cows occur more slowly than adjustment in physiological regulation of intake. Topp and Doyle (1994) account for this source of variation by altering the physical limit to intake during lactation. In the current model the influence of reproduction on intake is accounted for by specifying PMEI and a28 for different time periods during the year.

6.2.3.3 Pasture Availability Limit.

In the LP model, it is assumed that animals are able to graze pasture down to a minimum cover, below which further grazing is not possible. During model testing, however, placement of a limit on intake as a function of pasture availability had little value for improving estimates of intake. The poor predictive performance of the grazing limit is related to differences in temporal and spatial aggregation between the simulation models of Topp and Doyle (1994) and the LP model. The current study accounts for average monthly changes in pasture cover, but the model would need to include shorter time periods (such as a daily interval), and a smaller unit of spatial consideration (for example, a field), to adequately express the influence of forage availability on intake. In spite of its limited effectiveness, a pasture availability limit on intake was retained, to facilitate possible changes that would improve the resolution of the model. The form of this equation is as follows:

$$K_t \geq a30\ C_{pasture,t} \qquad (6\text{-}9)$$

where K is the amount of dry matter present in the field (kg DM), a30 is the minimum pasture cover that must be maintained in the field and hence is unavailable for grazing (kg DM hectare^{-1}); and C is the amount of land planted to a crop, in this case hectares of pasture. The coefficient a30 is estimated from the time series of Topp and Doyle (1994) as 600 kg hectare^{-1}.

6.2.3.4 Discussion.

The approach of Topp and Doyle (1994) is similar to that of the LP model with regard to intake. Topp and Doyle calculate intake of pasture dry matter as a minimum function of physiological and physical limits, and a limit based on the availability of forage. The physiological limit to intake is calculated by summing maintenance and pregnancy with the potential requirements for lactation and tissue growth. The resulting value is multiplied by a correction factor, from ARC (1980), to account for non-linearities between energy retention and intake levels. Topp and Doyle relate physical limits to intake to feed digestibility, animal liveweight, and rumen capacity. The size of the animals rumen, is in turn, modified with progress of lactation. Topp and Doyle allow for concentrate feeding, by adjusting the physical and physiological limits to intake. The simulation model also accounts for preferential selection of pasture by animals, predicting the proportion of the diet comprised of leaf, stem and dead material.

The complexity of the relationships included in Topp and Doyle's (1994) models tends to be greater than those present in the LP models. However, the principle difference in the scope of the LP models versus Topp and Doyle's models in terms of pasture intake, is that there is no provision to allow animals to make a constrained selection between leaf, stem and dead material in a sward. The LP allows animals to select between pasture and a range of other feed-stuffs, but for reasons of simplicity, the LP models pasture as a single pool of dry matter. In the LP model, the composition of the selected pasture diet is assumed to conform to the average of the diet predicted by the simulation models for each modelled sward (grass or grass / clover) and time period.

6.2.4 Lactation.

A variety of curves including the Wood's curve have been used to empirically describe lactation (Neal and Thornley, 1983; Wood, 1967). For dairy cows, the estimates of potential milk production are estimated from the time series data generated by Topp and Doyle's (1994) model. Topp and Doyle base their predictions on a gamma function described by Wood *et al* (1980). In the current model, potential milk production is constrained by the potential intake of metabolisable energy and by the proportion of energy intake allocated to lactation. The production of milk is calculated as:

$$L_t = \sum_{j=1}^{4} \sum_{k=1}^{2} \frac{kl\,(1 - a25_{t,j,k})\, MEI_{t,j,k}}{a31} \qquad (6\text{-}10)$$

where L is the amount of milk produced (litres); kl is the efficiency of utilisation of metabolisable energy for lactation; and a25 is the proportion of energy allocated to liveweight gain; a31 is the energy content of milk (MJME. litre milk^{-1}). From Beever and Oldham (1986); kl is taken as 0.63 and from ARC (1980) a18 is taken as 3.1.

In the sheep LP model, lactation is not explicitly modelled. Rather it is assumed that the influence of a sheep's lactation on other physiological processes is accounted for by reducing the proportion of energy intake allocated to liveweight change (see a25 in Equation 6-3) for a period of 3 months from the time that lambs are born. After this, it is assumed that lambs have been weaned. While lambs are suckling, it is assumed that the physiological requirements of the lamb are satisfied by the dams milk supply. In the sheep and dairy models, pregnancy is assumed to be a nutritionally non-responsive process that is additive with maintenance in terms of its influence on inter-period weight losses.

6.2.5 Energy Allocation.

The determination of energy allocation between alternate physiological processes and the method of estimating liveweight change, is handled differently in the simulation models compared with the current study. In Topp and Doyle's (1994) model, maintenance and pregnancy are treated as nutritionally non-responsive requirements, with maintenance calculated as a function of animal liveweight, age and level of production. With regard to pregnancy, Topp and Doyle assume that requirements are a function of the time since conception (ARC, 1980). Metabolisable energy that remains after maintenance and pregnancy have been accounted for is allocated to milk production and changes in liveweight.

In the simulation models, if energy intake is equal to the amount potentially required by the animal, then milk production and growth in liveweight proceed at potential rates. However, when energy intake is less than the amount required for potential lactation and animal growth, the amount of energy allocated to weight gain and lactation is reduced by an equal amount for each process. The requirement that reductions are equal, is subject to a non-negativity constraint on lactation. In situations where lactation would fall below zero, if the non-negative constraint were not present, the energy allocated to tissue growth is adjusted to reflect any shortfall. If the energy balance equations indicate a negative amount of energy is available for animal growth, the animal will catabolise tissue to provide energy for other metabolic processes. The method of determining the allocation of energy is empirically based, but is relatively simple and produced acceptable results when predicting milk production and liveweight change (Topp *pers. comm.*, 1995).

In this study, it is assumed that the amount of energy given to growth in liveweight and milk production is a proportion of the energy available for allocation. The actual proportion of energy that is allocated is determined using a pieci-linear approximation of a function representing the relative ability of the respective processes to obtain energy from the pool of ingested metabolisable energy. The variables $a25_{t,j,1}$ and $a25_{t,j,2}$ are critical to the calculation of energy allocation and are established using an iterative procedure to minimise differences between the LP models and the simulation models. Specifically the values of $a25_{t,j,1}$ and $a25_{t,j,2}$ are varied between 0 and 1 using a numerical procedure and substituted into the equations presented in this chapter. The resulting values of $a25_{t,j,1}$ and $a25_{t,j,2}$ are presented in Table 6-8 and Table 6-9.

The measure of difference between predictions of the LP models and simulation models is calculated as the sum of square differences between the two models as:

$$\min(u_{j,t}) = \sum_{o=1}^{obs} \left(\frac{L_{SIM\ t} - L_{LP\ t}}{\sum_{o=1}^{obs} L_{SIM\ t} / obs} \right)^2 + \left(\frac{\Delta LW_{SIM\ t,j} - \Delta LW_{LP\ t,j}}{\sum_{o=1}^{obs} \Delta LW_{SIM\ t,j} / obs} \right)^2 \qquad (6\text{-}11)$$

where u is the sum of squares that is minimised; o is the observation number; and obs is the number of observations. The subscripts SIM and LP refer to estimates

Table 6-8. Proportion of Metabolisable Energy Allocated to Tissue Growth. ($a25_{t,j,1}$ see Equation 6-3)

Beef.

	Class 1	Class 2	Class 3	Class 4
January	1	1	1	1
February	1	1	1	1
March	1	1	1	1
April	1	1	1	1
May	1	1	1	1
June	1	1	1	1
July	1	1	1	1
August	1	1	1	1
September	1	1	1	1
October	1	1	1	1
November	1	1	1	1
December	1	1	1	1

Dairy.

	Class 1	Class 2	Class 3	Class 4
January	1	1	1	1
February	1	1	1	1
March	1	1	1	1
April	0.54	0.54	0.54	0.54
May	0.54	0.54	0.54	0.54
June	0.54	0.86	0.96	0.96
July	0.77	0.82	0.87	0.87
August	0.72	0.94	0.97	0.97
September	0.86	0.97	0.98	0.98
October	0.96	0.93	1	1
November	1	1	1	1
December	1	1	1	1

Sheep.

	Class 1	Class 2	Class 3	Class 4
January	1	1	1	1
February	1	1	1	1
March	1	1	1	1
April	0.90	0.90	0.90	0.90
May	0.93	0.93	0.93	0.93
June	0.95	1	1	1
July	1	1	1	1
August	0.96	1	1	1
September	1	1	1	1
October	1	1	1	1
November	1	1	1	1
December	1	1	1	1

Lambs.

	Class 1	Class 2	Class 3	Class 4
March	1	1	1	1
April	1	1	1	1
May	1	1	1	1
June	1	1	1	1
July	1	1	1	1
August	1	1	1	1
September	1	1	1	1
October	1	1	1	1
November	1	1	1	1
December	1	1	1	1

Table 6-9. Proportion of Metabolisable Energy Allocated to Tissue Growth. ($a25_{t,j,2}$ see Equation 6-3)

Beef Animals.

	Class 1	Class 2	Class 3	Class 4
January	1	1	1	1
February	1	1	1	1
March	1	1	1	1
April	1	1	1	1
May	1	1	1	1
June	1	1	1	1
July	1	1	1	1
August	1	1	1	1
September	1	1	1	1
October	1	1	1	1
November	1	1	1	1
December	1	1	1	1

Dairy Animals.

	Class 1	Class 2	Class 3	Class 4
January	1	1	1	1
February	1	1	1	1
March	1	1	1	1
April	0.64	0.64	0.64	0.64
May	0.63	0.5	0.5	0.5
June	0.72	0.19	0.1	0.1
July	0.32	0.27	0.22	0.22
August	0.42	0.15	0.14	0.14
September	0.3	0.15	0.16	0.16
October	0.16	0.2	0.16	0.15
November	0.22	0.2	0.2	0.2
December	1	1	1	1

Sheep.

	Class 1	Class 2	Class 3	Class 4
January	1	1	1	1
February	1	1	1	1
March	1	1	1	1
April	0.35	0.35	0.35	0.35
May	0.35	0.35	0.35	0.35
June	0.39	0.34	0.34	0.34
July	0.49	0.59	0.90	0.90
August	0.70	0.69	1	1
September	1	0.82	1	1
October	1	0.47	0.56	0.65
November	1	1	1	1
December	1	1	1	1

Lambs.

	Class 1	Class 2	Class 3	Class 4
March	1	1	1	1
April	1	1	1	1
May	1	1	1	1
June	1	1	1	1
July	1	1	1	1
August	1	1	1	1
September	1	1	1	1
October	1	1	1	1
November	1	1	1	1
December	1	1	1	1

produced by the simulation models and LP models. The division by the means of the simulated estimates gives equal weighting to liveweight change and milk production.

Both the current study and the approach of Topp and Doyle (1994) allow animals to gain and lose weight, and for animals that do not lactate (when $a25_{t,j,1}$ equals 1) the two methods of calculating energy allocation should produce the same results. For lactating animals, there are differences between the models in terms of allocating energy between milk production and tissue growth. However, it was found during model testing, that differences in the way that energy allocation is estimated tended to be small.

6.2.6 Discussion.

The structure of the animal models provides sufficient constraints to cater for elements that confer decreasing returns to size with respect to the objective function. However, some of the non-linear responses are concave with increases in animal weight; in particular, heavier animals can achieve higher sale prices per kilogram of liveweight than lighter animals. It would be possible to minimise interpolation errors by specifying integer variables that require animals to be placed in no more than two adjacent weight categories. A difficulty associated with including integer variables, is that the dual prices produced when the model is solved, are often numerically unstable, making it difficult to achieve a global optimum for a decomposed problem. In the current study it is unlikely that interpolation errors from this source will cause distortions to the solution, and for this reason integer variables are not included in the model.

6.3 Estimation of Management Parameters.

6.3.1 Introduction.

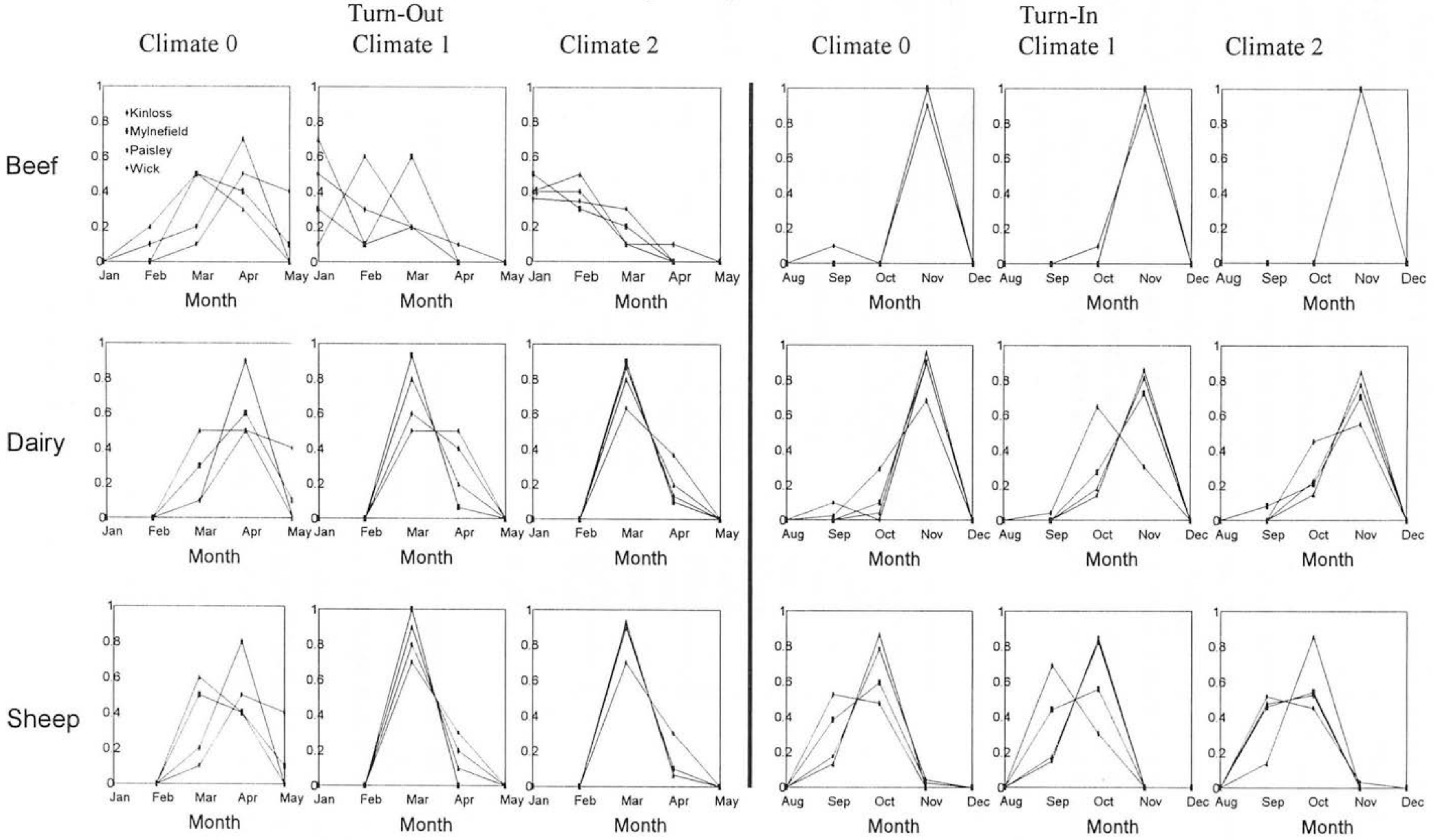
The dates that forage is conserved and animals are turned out in spring and yarded in autumn were initially estimated for each of the grass and grass / clover models, climates, regions, soils, animal types and stocking rates that are considered by Topp and Doyle (1994). In these scenarios the factors that are varied by Topp and Doyle are each represented at a single level. This differs from the current study, where grass and grass / clover and sheep and cattle can be present on a single farm and four soil types are defined for each farm type. Also, stocking rate is treated as an endogenous variable in the LP model, rather than as an exogenous variable as in Topp and Doyle's scenarios. In the current study, it is necessary to adopt simplifying assumptions to resolve possible conflicts in the timing of events relating to forage conservation and animal housing. In the following sections the parameters associated with the turn-out and yarding of animals and forage conservation are presented.

6.3.2 Turn-out Dates.

The method of modelling animal turn-out and turn-in involves specifying the periods when the pasture type present on a particular soil can be consumed by animals and by defining when animal housing is required. To simplify the specification of the LP model, the turn-out and turn-in dates are calculated for each region, climate, and animal type as the respective mean of the pasture and soil types and intermediate stocking rates that are considered. This method of determining whether animals require housing or are being kept outside on pasture is slightly arbitrary, as there is no requirement in the model for the pasture and soil type that determine the dates of housing to be present in the farm plan.

Although differences exist between the grass and grass / clover swards in terms of the amount of pasture accumulating in the sward at different times of the year, differences in the timing of turn-out and turn-in (which are determined by rules relating to herbage mass) were largely eliminated when aggregating Topp and Doyle's (1994) daily data to the monthly period considered in the LP model. Similarly, differences between soils tended to be removed when aggregating from daily to monthly intervals. The proportions of months that animals are turned out and turned in from pasture can be found in Figure 6-3; the turn-out and turn-in dates that are used in the model runs are presented in Table 6-10 and Table 6-11

Figure 6-3. Proportion of Turn-out and Turn-in Dates Occuring in Respective Months



From Figure 6-3 it can be seen that climate change has a large influence on the month that beef animals are turned out for grazing. Under current climatic conditions (climate ‘0’) beef animals are turned out predominantly in March and April. In contrast beef cattle tend to be turned out earlier for climate ‘1’, with January and February and to a lesser extent March becoming the principle months that grazing commences. The trend for turning out animals earlier in the year is also evident when comparing climate ‘0’ with climate ‘2’. For climate ‘0’, the regions are ranked in terms of earliest to latest turn-out as follows: Paisley, Mylnefield, Kinloss and Wick. This ranking conforms to expectations, as the regional ordering approximates a gradient in average temperatures between a relatively warmer south-west and a cooler north-east (see Section 2.2).

Table 6-10. Turn-out Dates.

Region	Climate	Animal Type		
		Beef	Dairy	Sheep
Kinloss	‘0’	April	April	April
	‘1’	February	March	March
	‘2’	February	March	March
Mylnefield	‘0’	March	April	March
	‘1’	March	March	March
	‘2’	February	March	March
Paisley	‘0’	March	March	March
	‘1’	February	March	March
	‘2’	February	March	March
Wick	‘0’	April	April	April
	‘1’	February	March	March
	‘2’	February	March	March

A comparison of climate ‘1’ and climate ‘0’ shows that the grazing season begins earlier and a relative change in the order of regions occurs. For climate ‘1’ the regions are ranked as follows: Paisley, Kinloss, Mylnefield and Wick. For climate ‘2’, there is little difference between the turn-out dates that occur in the different regions. The average turn-out date for Paisley and Kinloss are similar to that found for climate ‘1’, while for Mylnefield and Wick the turn-out date is earlier for climate ‘2’ than for climate ‘1’.

Given the current climate at Paisley, dairy animals are turned out in March in half of the years, and at Wick animals are turned out in May approximately four years out of ten. At these sites, in other years, and for the other regions, April is the principle month that dairy animals are turned out. Compared with climate ‘0’, the turn-out dates for dairy cows advance by approximately a month for climates ‘1’ and ‘2’. For all four regions the turn-out dates are quite different for climate ‘0’ compared with climates ‘1’ and ‘2’. The regional rankings for climate ‘0’ with respect to the average turn-out dates for dairy animals is the same as for beef cattle. For climate ‘1’, Wick becomes the earliest month that dairying animals are turned out, followed by Paisley, Kinloss and Mylnefield. This result is contrary to expectations but corresponds to the ranking found by Topp and Doyle (1994) for grass swards and is similar to the ranking for grass / clover (see Tables 47 and 55 in Topp and Doyle, 1994).

The advance in the average turn-out dates with a change in climate is less for sheep than for beef cattle. For climates ‘1’ and ‘2’, therefore, the average date that sheep are turned out is intermediate between beef cattle, and dairy animals. For all climatic scenarios, dairy cows are the last animals to be turned out. For the current climate, at all sites except Wick, sheep are turned out to pasture primarily in March and April. At Wick, turn-out is later and occurs predominantly in April and May. For climates ‘1’ and ‘2’, in all regions March is the principle month that sheep commence grazing. The ranking of regions in terms of the commencement of grazing is similar for sheep and dairy cows.

6.3.3 Turn-in Dates.

Climatic change has a lesser influence on turn-in dates than on the timing of turn-out. In particular, an increase in temperature such as occurs between climate ‘0’ and climate ‘1’, has little effect on the time that beef animals are turned in. With regard to dairy and sheep, a change in climate from current conditions to climates ‘1’ or ‘2’ results in a number of small changes to the timing of turn-in and in some cases results in an advance in the date of turn-in. As mentioned in Section 2.2 this result is contrary to expectations but is consistent with the relative changes in potential pasture that are estimated for the climate and regional scenarios that are considered.

For all climates, regions and years, beef cattle are principally yarded in November and in the majority of regions the yarding of dairy animals also occurs in November. An exception to this is Kinloss where dairy animals are yarded in October as well as November. At Kinloss for both climate change scenarios (climates ‘1’ and ‘2’), the proportion of years that animals are turned out in October is greater than in climate

'0'. The yarding of dairy animals at Kinloss is therefore earlier on average for changed climatic conditions than for the current climate.

Sheep tend to be yarded earlier than dairy or beef animals. At Mylnefield and Paisley there appears to be little difference between the climates with respect to turn-in dates. At Kinloss a greater proportion of sheep are turned in during September for climate '1' than for climate '0'. This contrasts with climate '2' where sheep are turned in slightly later for the changed climate. At Wick there is little difference between climates '0' and '1' in the timing of the end of the grazing period, but between climates '0' and '2', turn-in dates advance by approximately a month.

Table 6-11. Turn-in Dates.

Region	Climate	Animal Type		
		Beef	Dairy	Sheep
Kinloss	'0' '1' '2'	November November November	November October November	September September October
Mylnefield	'0' '1' '2'	November November November	November November November	October October October
Paisley	'0' '1' '2'	November November November	November November November	October October October
Wick	'0' '1' '2'	November November November	November November November	October October September

6.3.4 Forage Conservation.

The models of Topp and Doyle (1994) include a rule base that allows fields to be opened or closed for conservation depending on the amount of pasture that is present in the field. The rule base also allows fields to be cut for silage either on a particular date or on the basis that the amount of pasture in a field exceeds a certain amount. With respect to this study it is assumed that all fields that are closed for conservation are cut on June 1 and October 1. This assumption is adopted regardless of the system being considered.

6.3.5 Discussion.

Not all of the between year differences that are discussed with respect to the timing of turn-out and yarding are apparent when considering the dates that are actually included in the LP model (see Table 6-10 and Table 6-11). The loss of information is partly due to the aggregation of the time series data from Topp and Doyle's (1994) model to a single year time horizon and is aggravated by the process of discretising Topp and Doyle's daily data to provide the monthly time step present in the LP model. The amount of information that is retained regarding the timing of the grazing period could be increased, either by utilising a smaller time step or by extending the number of years that are included in the LP model. If these changes were implemented, there would be issues associated with integrating the changes with other components of the model. In any case the aggregation errors that are present in the animal LP model are unlikely to be more serious than errors in other parts of the model.

Further, changes in the duration of the grazing period tend to reflect changes in the growth rates of pasture. The errors involved with estimating the dates of turn-out and yarding may not have as large an impact on the overall model solution as would occur if the grazing period was the only measure of pasture productivity. The LP model reproduces simulated changes in pasture growth rather better than variations in the timing of the grazing period. This is because the LP model is able to represent changes in growth rates using continuous variables, whereas the duration of the grazing period is defined by the presence of discrete variables. The LP model should, therefore, capture the major changes in pasture productivity.

With respect to forage conservation, it would be possible to vary the dates that fields are cut for hay or silage and also to consider issues such as machinery scheduling and the influence of weather on forage losses. Although, the spatial and temporal aggregation of the LP model is not entirely appropriate to address issues such as these, the structure of the LP model could be readily adapted to address these types of issues. Further, it is only likely that changes of this kind would be introduced if the individual farm models were used in a farm and year specific analysis.

7. MACHINERY, BUILDINGS, LABOUR AND FINANCE.

7.1 Machinery and Buildings.

The purchase of machinery and buildings represents a large and relatively inflexible component of farm investment. The model as it is currently specified, determines the optimal level of ownership of different types of buildings and plant. The method used to calculate the annual cost of plant ownership is described by Frengley (1983a and 1983b). The opportunity cost of capital, a monthly sinking fund to finance eventual replacement, repairs and maintenance, and licence fees and insurance are taken into account. The effects of taxation and inflation on decisions that relate to the timing and level of capital purchases and sales is not considered in the analysis as these are highly dependent on the financial situation of individual farmers and involve considerations that extend over longer periods than the single year time horizon of the model.

The machine types that are represented in the model include the following: tractor, plough, disk harrow, light dutch harrow, power harrow, roller, conventional drill, combined seed and fertiliser drill, fertiliser broadcaster, sprayer, combine harvester, trailer, mower, tedder, windrower, baler, forage harvester and wagon, potato ridger, planter and harvester, farm yard manure spreader, stone picker and irrigator. The building types that are specified are: hay barn, grain and concentrate store, silage pit, potato store and animal housing. Allowance has also been made for field operations to be carried out by contractors and for farms to provide contracting services. Parameters relating to estimates of various costs, productivity's and capacities associated with machinery and labour are derived from a number of sources; these include Agro-Business Consultants (1995), SAC (1994), Cooper *pers. comm.*, (1995) and Saadoun (1989).

In the farm level models the majority of machinery types are included at three sizes and a single size of each building is represented. A description of the machines and buildings that are present in the matrix is presented in Appendices 4.1 and 4.2. The machines and buildings that can enter a farm plan are subject to a constraint that they must be appropriate to the activities of the respective farm type. For example animal housing activities are not represented on pure 'cropping' farms. Other machines and buildings not included on 'cropping' farms are: forage harvesters, forage wagons, farm yard manure spreaders, silage pits, and sheds for storing concentrates. On farm types that do not involve cropping (that is 'cattle and sheep' farms, 'dairy' farms and 'sheep' farms), machines and buildings that are involved with the planting, irrigation, and harvesting of crops are excluded from the respective sub-matrices. The 'cropping and cattle' farm type involves both animal and cropping activities and includes all of the machinery and building activities that are represented in the model.

With the exception of self propelled machines (that is tractors, combine harvesters and windrowers) the machinery implements that are included in the LP model must be linked to a tractor to operate. In general it is assumed that the largest tractor (tractor '1') can be coupled to any of the implements (implements '1'-'3'), the second largest tractor (tractor '2') can be attached to the second or third largest of the implements (implements '2' and '3'), and the smallest tractor (tractor '3') can only be attached to the smallest implement (implement '3'). However, for some implements the above rules are not appropriate; these include trailers, conventional hay balers, forage wagons, potato ridgers, stone clod separators, stone / clod windrowers, and irrigators. For details of the tractors that implements can be attached to refer to Appendix 4.1.

An example sub-matrix that represents two sizes of tractor and plough and three time periods is presented in Figure 7-1. From Figure 7-1 it can be seen that the following factors are specified for the tractors and implements: the availability of tractor and ploughing hours, work rate, requirements for labour, fuel consumption and expenditure that relates to the purchase of the machines and also to running costs (excluding fuel) and repairs and maintenance that vary with machine usage. The number of tractor and ploughing hours that are available to perform machinery operations are estimated by assuming that machines can operate a maximum of 80 hours per week. It should be noted that the number of hours that a machine is available to work does not reflect the suitability of the weather or ground conditions to perform a machinery operation. Rather the influence of weather on the amount of time that is available to perform an operation is accounted for in the specification of workable hours (for further details, see Section 7.1.1).

Figure 7-1. Machinery[106].

			Purchase				Operate		
			Tractor		Plough		Tractor 1 & Plough 1	Tractor 1 & Plough 2	Tractor 2 & Plough 2
			1	2	1	2			
Tractor 1 Hours	0	≥	-A[107]				1 [108]	1 [108]	
	0	≥	-A				1	1	
	0	≥	-A				1	1	
Tractor 2 Hours	0	≥		-A[107]					1 [108]
	0	≥		-A					1
	0	≥		-A					1
Plough 1 Hours	0	≥			-A[109]		1 [108]		
	0	≥			-A		1		
	0	≥			-A		1		
Plough 2 Hours	0	≥				-A[109]		1 [108]	1 [108]
	0	≥				-A		1	1
	0	≥				-A		1	1
Plough Field	0	≥					-A [108]	-A [108]	-A [108]
	0	≥					-A	-A	-A
	0	≥					-A	-A	-A
Labour	0	≥					1 [108]	1 [108]	1 [108]
	0	≥					1	1	1
	0	≥					1	1	1
Fuel	0	≥					A [108]	A [108]	A [108]
	0	≥					A	A	A
	0	≥					A	A	A
Working Capital	+/-A	≥	A[110]	A[110]	A[110]	A[110]	A [108]	A [108]	A [108]
	+/-A	≥	A	A	A	A	A	A	A
	+/-A	≥	A	A	A	A	A	A	A

Work rates are defined for the majority of machinery operations in units of hectares per hour. For a particular task, therefore, a given number of hectares will be completed for each hour that a machine is operating. For fertiliser broadcasters and farm yard manure spreaders, work rates are defined in tonnes of fertiliser or manure that are spread per hour and the work rate of a combine harvester is defined as the number of tonnes of matter other than grain (MOG) per hour that can be processed (see Section 5.2.3). The requirement for labour and fuel is therefore dependent on the amount of material that is spread or the amount of MOG that is in a field. In the case of tractors and trailers it is assumed that for each hour a combine harvester or conventional hay baler is working that two hours of tractor and trailer time are

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[106] 'A' refers to non-zero coefficients that are not equal to unity. Note: in the actual matrix three sizes of tractor and plough and 12 time periods are represented.

[107] Available tractor hours (up to 80 hours per week).

[108] Operate tractor and plough combination. Each hour of operation requires 1 hour of labour, fuel and working capital (to cover running costs (excluding fuel and labour) and repairs and maintenance) and ploughs a given amount of land (see Appendix 4-1).

[109] Available plough hours (up to 80 hours per week).

[110] Working capital requirements associated with machinery ownership.

required in the same time period. Another assumption is that the amount of fertiliser applied by a combination fertiliser and seed drill (up to a maximum of 250 kilograms per hectare) has no effect on the rate of seeding operations. Rather it is assumed that the per hectare rate of seeding by a combination fertiliser and seed drill is a function of the size of implement.

Some other points that relate to tractors and attached implements are the rate of a tractors fuel consumption is dependent on the size of tractor and does not vary with different types or sizes of implements or soil types. Further, it is assumed that the work rates of implements are functions of the size of implement and do not vary with the size of the attached tractor or soil type. The assumptions relating to work and fuel consumption rates are adopted for reasons of simplicity. However, it would be relatively straight forward to make the necessary modifications to the LP model if variations of this type were considered in a future study. In the case of modelling fuel consumption or work rates that depend on the actual tractor and implement that are attached together, the LP could be updating simply by modifying the coefficients that reflect these factors. However, if variations between soils in work or fuel consumption rates are considered - activities and constraints that represent the machine operating on individual soils would need to be included in the LP model. Although these changes would not be difficult to introduce they would involve an increase in the size of an already large matrix.

The capacity of buildings that provide storage for hay, straw, grain and concentrates are defined in units of cubic metres. Similarly the amount of animal housing space that is required varies depending on the type of animal being considered and the size of the silage pit and potato store are defined in tonnes. The method used to represent the provision of milking facilities is slightly different to that adopted for other buildings in the model as the dairy parlour is not explicitly represented. Rather the costs associated with the provision of a dairy parlour is treated as an overhead that is attached to the annual cost of owning a cow. The costs associated with different sized buildings are included in Appendix 4.2.

7.1.1 The Effect of Weather on Machinery Operations.

In the LP model the influence of weather on the availability of working hours to perform different operations is considered. Weather impacts on soil moisture and can cause difficulties for machinery that are put on wet soils. Other weather variables such as wind and humidity can also cause problems for spraying and harvesting operations (Cooper and McGechan, 1994). Changes in weather conditions that are associated with climate change may, therefore, affect the management of machinery operations and also the size of machinery complement that is required to perform tasks associated with a farm plan.

A detailed simulation model of soil moisture and heat processes was developed by Jansson (1991) and subsequently adapted by Cooper and McGechan to study the influence of climate on soils and availability of workdays. The adaptations that Cooper and McGechan (1994) introduced to Jansson's (1991) model allowed the number of hours in each month that fields can be cultivated to be estimated as a function of soil moisture. Cooper and McGechan (1994) also used Jansson's model to consider the impact of weather on forage conservation and harvesting of arable crops (Cooper *pers. comm.*, 1995). The method that Cooper used to estimate the availability of crop harvesting days is taken from Witney and Eradat Oskoui (1982) and involved identifying days on which rainfall is less than a defined threshold. With regard to this study, the number of hours in each month that are available for cultivation and arable crop harvesting are estimated for each of the regions and climates that are represented.

In the current context, a cultivation operation is defined as one that involves any of the following implements: a plough, harrows, roller, seed drill, fertiliser spreader, potato ridger, potato planter, farm yard manure spreader or stone picker. Harvesting operations are defined as those that involve a combine harvester. The results of this analysis are presented in Appendix 10 and a summary can be found in Table 7-1. Although the impact of climate on other machinery operations (such as forage harvesting and crop spraying) are not considered in this study, factors such as these could be readily addressed using methods similar to those presented here (Cooper *pers. comm.*, 1995).

Figure 7-2. Workable Hours[111].

			Purchase		Operate Plough	Contract		Transfer Workable Hours Permission	
			Tractor	Plough		(In)	(Out)		
Availability of Tractor Hours	0	≥	-A[112]		1[113]		1[114]		
	0	≥	-A		1		1		
	0	≥	-A		1		1		
Availability of Ploughing Hours	0	≥		-A[115]	1[113]		1[114]		
	0	≥		-A	1		1		
	0	≥		-A	1		1		
Plough Field	0	≥			-A[113]	-A[116]			
	0	≥			-A	-A			
	0	≥			-A	-A			
Working Hours (Cultivation)	0	≥	-A[117]		1[113]			-1[118]	
	0	≥	-A		1			-1	
	0	≥	-A		1			-1	
Working Hours (Harvesting)	0	≥	-A[117]						-1[118]
	0	≥	-A						-1
	0	≥	-A						-1
Working Hours (Cultivation or Harvesting)	0	≥	-A[117]					1[118]	1[118]
	0	≥	-A					1	1
	0	≥	-A					1	1

The estimates of the number of workable hours that are available to perform different operations are included in the LP matrix as coefficients that are associated with the purchase of tractors (see Figure 7-2). The number of workable hours to perform cultivation and harvesting operations increases, therefore, with the number of tractors. An assumption that is inherent to the presented formulation is that the various field operations can be performed in parallel. Also, it is assumed that the tasks carried out by contractors do not reduce the amount of time that is available to farmers to carry out operations.

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[111] 'A' refers to non-zero coefficients that are not equal to unity. Note: in the actual matrix three sizes of tractor and plough and 12 time periods are represented.

[112] Available tractor hours (up to 80 hours per week).

[113] Operate tractor and plough combination. Each hour of operation requires labour, fuel, working capital (see Figure 7-1) and workable hours (which refer to the number of hours that are suitable, in terms of the weather, to perform different classes of tasks) and ploughs a given amount of land.

[114] Provide tractor and plough combination as a contracting service to other farmers.

[115] Available plough hours (up to 80 hours per week).

[116] Hire tractor and plough combination from a contracting service.

[117] Available workable hours or hours that are suitable in terms of the weather to perform different classes of tasks (that is cultivation, harvesting, or cultivation or harvesting).

[118] Transfer workable hours that are suitable for either cultivation or harvesting so that they are available for a particular class of tasks (that is cultivation or harvesting).

The number of workable hours that are available for each class of workable hours (that is cultivation, harvesting, or both) are estimated for each of the regions and climates considered in this study. The models implemented by Cooper and McGechan (1994) and Cooper *pers. comm.*, (1995) are used in conjunction with the synthetic weather series data provided by Peiris *pers. comm.* (1995). A further assumption is that the water holding capacity of soil type '2' provided a reasonable basis for estimating the number of workable hours that occur on the other soil types that are included in the model. This assumption is adopted as soil type '2' is the principle soil on which cropping operations occur. Further, an exploratory analysis with the soil moisture models showed that the number of workable hours is relatively insensitive to variations in soil water holding capacity.

The results of an analysis of variance that was performed on the estimates of workable hours is presented in Table 7-1. It can be seen that the availability of workable hours to perform cultivation operations is considerably greater than the number of harvesting hours. A comparison shows that approximately 5.6 to 14 times as many hours are available for cultivation as for harvesting. Kinloss has the most favourable climate in terms of availability of working hours and Paisley is the least favourable region; Wick and Mylnefield are intermediate to these regions. Paisley has approximately 60 percent of the cultivation hours and 30 percent of the harvesting hours that are available at Kinloss. A possible explanation for this is that the relatively high rainfall that occurs at Paisley has a deleterious effect on harvesting operations. However, differences in rainfall totals only explain some of the variations that are evident in Table 7-1.

At Kinloss there are no significant differences between climate '0' and the other climate scenarios for either cultivation or cultivation and harvesting hours. This contrasts with Mylnefield where there are no significant differences between climates for cultivation hours, but between climate '0' and climates '1' and '2' significant increases in the number of cultivation and harvesting hours are recorded. At Paisley a significant reduction in the number of cultivation hours is recorded for climate '1' when compared with climate '0'. A similar comparison between climates '2' and '0' showed no significant difference in cultivation hours. Also at Paisley there is no significant difference between climates '0' and '1' for cultivation and harvesting hours. At Wick there is no significant difference in cultivation hours between climates but a significant increase in the number of cultivation and harvesting hours is recorded between climate '0' and climate '1'.

Table 7-1. Average Number of Workable Hours and Significance of Differences between Climate ‘0’ and Climates ‘1’ and ‘2’ (hours. year^{-1})[119].

Region	Kinloss			Mylnefield		
Climate	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’
Cultivate	2457	2247 n.s.	2610 n.s.	1920	1794 n.s.	2202 n.s.
Harvest	0	0 n.s.	0 n.s.	0	0 n.s.	0 n.s.
Cultivate or Harvest	465	480 n.s.	411 n.s.	204	294 **	303 **
Region	Paisley			Wick		
Climate	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’
Cultivate	1650	1383 **	1560 n.s.	2184	2334 n.s.	2286 n.s.
Harvest	0	0 n.s.	0 n.s.	0	0 n.s.	0 n.s.
Cultivate or Harvest	153	144 n.s.	120 **	219	219 n.s.	369 **

The variable pattern of changes in working hour availability suggests that the above results may have been caused by interactions between a number of weather variables. Further, the estimates of workable hours are dependent on processes that occur during intervals that are much shorter than the monthly interval that is reported (for example daily or hourly periods) (McGechan *pers. comm.*, 1995). Changes in the average value of weather variables do not, therefore, provide a good indication of changes that are related to rapidly changing processes. The results suggest that simple conclusions relating changes in the availability of cultivation and harvesting hours to broad estimates of changes in climatic variables are not appropriate. Rather the estimates of changes in working hours must be specific to the climate and location that are being considered.

7.2 Labour.

Farm labour is supplied by permanent employees and may be supplemented by overtime and hiring of casual labour on an hourly basis. The labour requirements are modelled for individual machinery operations and for tasks such as livestock feeding,

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[119] n.s. = not significant, ** = significant at 95 % confidence level.

milking and lambing. The number of hours that are required to perform machinery operations depends on the amount of work that needs to be done and on the work rate of the machines that are selected in the farm plan. For the activities associated with animal husbandry, labour requirements are specified as the number of hours per month that are required for each animal type. For beef cattle, dairy cows, and sheep it is assumed that 1.2, 4.8 and 0.3 hours of labour are required per animal per month (Barton *pers. comm.*, 1995)

In the model family labour is not differentiated from permanent or hired labour. An assumption, therefore, is that the cost of family labour is the same as hiring either a permanent employee or a casual labourer. It is assumed that a full time employee supplies 40 hours of labour per week and is able to work overtime a further 20 hours per week. The annual cost of hiring a full time farm labourer is taken as £ 9200.00 and it is assumed that overtime and casual labour cost £ 5.50 per hour (SAC, 1994). A further point is that the number of permanent employees that can be hired by the various farm types is not constrained. However, to avoid solutions that are dominated by casual labour it is assumed that there is an upper limit to hiring casual labour. The magnitude of this limit is estimated from 1995 farm accounts data for the different farm types (see Table 7-2) and included as right hand side coefficients in the model (see Appendix 3.3). An example sub-matrix that illustrates the methods that are used to model labour can be found in Figure 7-3.

Table 7-2. Maximum Casual Labour Hours.

Farm Type	Casual Labour
'Cattle and sheep'	175
'Dairy'	267
'Sheep'	345
'Cropping'	1105
'Cropping and cattle'	498

Figure 7-3. Labour Supply Sub-matrix[120].

			Fixed Labour	Overtime Labour			Casual Labour		
Labour	0	≥	-A[121]	-1		[122]	-1		[123]
	0	≥	-A		-1			-1	
	0	≥	-A			-1			-1
Overtime Labour	0	≥	-A[124]	1		[122]			
	0	≥	-A		1				
	0	≥	-A			1			
Maximum Casual Labour	A[125]	≥					1	1	[123] 1
Working Capital	+/-A[126]	≥	A[127]	A		[128]	A		[129]
	+/-A	≥	A		A			A	
	+/-A	≥	A			A			A

7.3 Working Capital.

As the model only considers a single year time horizon it is not possible to satisfactorily address issues that are associated with long term changes in financial status. Rather an effort is made to model the influence of alternate plans on the cash or working capital position of farms. In the model financial transactions are accumulated as monthly cash flows and farm profitability is estimated from the working capital that is available at the end of the year. During periods of positive cash flow a current account is represented and an overdraft facility supplies cash during periods of negative balance. The funds available to farmers at the start of the year is calculated from estimates of short term assets and debts and is represented in the model as the right hand side coefficient of the respective working capital constraint. The objective function of the model is to maximise the end of year sum of working capital for the farm types and regions that are considered.

Included in the estimate of the amount of working capital at the start of the year is

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[120] 'A' refers to non-zero coefficients that are not equal to unity.

[121] Labour supplied by 1 full time labour unit.

[122] Supply overtime labour.

[123] Supply casual labour.

[124] Maximum availability of overtime labour.

[125] Maximum availability of casual labour.

[126] Coefficients relate to available funds at the start of the year and also to off-farm income and repayments of interest and principal on borrowings (see Section 7.3).

[127] Cost of hiring a full time labour unit.

[128] Cost of overtime labour.

[129] Cost of hiring casual labour.

the cash that farmers hold, funds that can be readily withdrawn from the bank, money that is owed to the farm by debtors, less overdraft facilities that have been utilised and money owed to creditors. The financial transactions that are represented in the model include the purchase of inputs and sale of outputs from the crop and animal systems. With respect to machinery, buildings and capital livestock, the cost of owning these assets are included as annualised costs[130] that vary depending on the number and size of assets that are selected in the farm plan (see Figure 7-4).

Long term debt is incorporated by including coefficients on the right hand side of working capital constraints that relate to repayments of interest and principal on borrowings. Further, it is assumed that income received from off-farm investments reduces the net level of these repayments. The inclusion of these values improves the ability of the model to estimate the magnitude of farm cash flows, however, the method is not suited to evaluating changes in debt and asset structure that extend beyond the single year time horizon of the model. To evaluate changes of this type longer term financial instruments would need to be explicitly included in the model and also the time horizon of the model should be extended to encompass a number of years of farming operation. Although these extensions would not be difficult to implement they would involve a considerable increase in the size of the model and therefore are not considered in this study.

Figure 7-4. Finance Sub-matrix[131].

			Current Account	Overdraft	Purchase Inputs	Sell Outputs
Working Capital	+/-A[132]	≥	1 [133]	-1 [134]	A [135]	-A [136]
	+/-A	≥	-A 1	A -1	A	-A
	+/-A	≥	-A 1	A -1	A	-A
Objective Function	(max)		1	-1		

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[130] The method of calculating the annualised cost of ownership accounts for the opportunity cost of capital, a monthly sinking fund to finance eventual replacement, and annual costs such as repairs and maintenance, licence fees and insurance.

[131] 'A' refers to non-zero coefficients that are not equal to unity.

[132] Coefficients relate to available funds at the start of the year and also to off-farm income and repayments of interest and principal on borrowings.

[133] Interperiod transfers of positive cash balance (A refers to principal plus interest that is recieved).

[134] Interperiod transfers of negative cash balance (A refers to principal plus interest that is paid).

[135] Cost of inputs are included as working capital requirements.

[136] Revenues recieved from the sale of outputs supply working capital.

The interest rate on the current account is assumed to be 0.5 percent per month (or approximately 6 percent annually) and the interest rate applying to overdraft facilities are assumed to be 1.2 percent a month (approximately 15 percent per year). The financial status of the various farm types are estimated from the Farm Accounts Scheme data (see Table 7-3) and are included in the model as coefficients on the right hand side of the working capital constraints. In the model the funds that are available at the start of the year increment the right hand side coefficients that relate to January working capital constraints. The payments associated with fixed debts are made as equal quarterly instalments in March, June, September and December. Also, the timing of the payments associated with purchasing machinery, buildings and capital livestock are assumed to be the same as those applying to fixed debts.

When estimating the funds available at the start of the year a difficulty is that the FAS relates to the financial year of the contributing farmers (and may vary anywhere between November and May) but in the model the year starts in January. For accounting reasons the FAS year corresponds to the tax year of the contributing farmers, but in the model taxation is not considered. Rather, the model is started at a time of the year that is relatively quiet with respect to production. However, the differences in cash availability between the commencement dates of the FAS and the model should not be large (Anderson *pers. comm.*, 1995). Another difficulty involving the FAS data is that it is not possible to identify the source of a debt. It is assumed therefore that all long term debt payments are associated with land and that farms are sufficiently capitalised that purchases of machinery, buildings and capital livestock are funded from working capital.

The analysis of the FAS data showed that on average 'sheep' farms hold the most funds at the beginning of the year and have the lowest net repayments on fixed debts. In contrast 'cropping and cattle' farms have the least funds on hand and the greatest level of debt repayments. The ranking of the farm types having the greatest to the least amount of funds is almost identical to the ranking achieved by farms with respect to the level of debt repayments. In general the farm types that involve cropping activities are the most indebted and hold the least funds while farms that involve sheep activities are the least indebted and have the greatest available funds. 'Dairy' farms tended to be intermediate to these other farm types. The financial status of farms appeared to be relatively less influenced by the presence of cattle.

Table 7-3. Financial Status of Farm Types (£. farm^{-1})

Farm Types	Funds Available at Start of Year	Net Repayments of Fixed Debt
'Cattle and sheep'	4925	5160
'Dairy'	5690	7770
'Sheep'	10150	2250
'Cropping'	4890	9590
'Cropping and cattle'	2120	15125

8. VALIDATION OF MODEL PARAMETERS.

8.1 Introduction.

The evaluation of a model normally involves a series of formal and informal tests to identify and correct deficiencies in a models structure and allow conclusions to be formed about the ability of a model to achieve its stated objectives. Model evaluation is an essential step in the modelling process as untested models contribute little to the understanding of real systems (Dent and Blackie, 1974). Given the importance of model evaluation, the techniques that are used to test models have received considerable attention in the literature. In a review of testing procedures, Harrison (1987) questioned the value of some commonly used statistical techniques. Harrison showed that a simultaneous test of zero intercept and unit slope for linear regressions of model and real system output can be misleading and violate assumptions of statistical inference. Instead, Harrison suggests that graphic comparison and subjective evaluation may provide a better test of model performance. The methods used to test the models in this study, therefore, are principally subjective techniques.

The chapter is in two parts. In the first part - the crop and pasture models are considered. The simulation models that are used to predict changes in the production of potatoes, wheat and grass and grass / clover have been extensively tested for British conditions. As a relatively high degree of confidence can be placed in these models, they are used in this study without further validation. In contrast Kvifte's (1987) model was developed for Scandinavian conditions; also the structure of Kvifte's model was altered as part of this study to account for the influence of temperature on crop development. It is important therefore to evaluate the predictive performance of Kvifte's model against Scottish trial data. The results of this comparison and conclusions relating to the suitability of this model to provide input to the current study are discussed in Section 8.2.1. The ability of a subset of linear equations from the LP model to reproduce variations in Scottish trial data are presented in Sections 8.2.2 and 8.2.3. In particular, the influence of nitrogen on crop yield and pasture is considered.

In the second part of the chapter the predictive performance of the animal models is examined. The outputs from a subset of the equations that are included in the linear programming models of the animal production systems are compared with predictions produced by Topp and Doyle's models. The presented outputs do not purport to be a formal validation of the linear programming model, instead a more modest goal of illustrating the ability of the LP model to mimic and interpolate between the outcomes of the simulation models for a range of conditions is attempted.

8.2 Crop and Pasture Models.

The linear programming models are designed to describe the bio-physical responses of crops to a selected set of management and environmental variables. Environmental factors that vary between the climates, regions and soils considered in this study, but which are not explicitly represented in the LP model, are assumed to be reflected in the estimates of potential crop productivity's. To an extent this reduces the complexity of the LP model and hence the requirement for determining the validity of the LP models is less than if all of the factors in the simulation models are present in the LP model. The estimation of parameters from simulated time series data does, however, present difficulties in terms of establishing confidence in the LP model, as any errors in the time series will also be present in the parameters that are estimated from these series.

8.2.1 Evaluation of Kvifte's Model.

Although a considerable amount of trial data is published in the literature, only a small proportion is suitable for evaluating the performance of simulation models. Often the values of experimental inputs that are omitted from discussion are critical to the prediction of observations; also data presentation is sometimes incomplete, so that detailed comparisons between experiments and model output are not always possible (McCall, 1984; Vera *et al*, 1977). The trials against which Kvifte's model is evaluated were collected from a series of annual reports produced by the Scottish Agricultural College[137]. The reports from which the trial data was taken were published between 1967 and the last report of the series which was produced in 1990. A listing of these reports is included in Appendix 8. The reports provide a valuable source of data as the experiments were conducted at various locations in Scotland and include detailed accounts of experimental inputs and results. Further, the reports involve a relatively wide range of crops, sites and experimental factors

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[137] The Scottish Agricultural College, Edinburgh was called East of Scotland College of Agriculture prior to 1987.

With the exception of vining peas, the trials were selected on the basis that the following information is reported: year, site, soil type, dates and amounts of nitrogen fertilisation, sowing date, harvest date, and crop yield. As vining peas are a leguminous crop, information relating to the level of nitrogen fertilisation was not collected or used as criteria for selection. From each trial, the highest yielding replicate for each soil type, harvesting and sowing date and (excepting peas) nitrogen treatment is selected; this was done as lower yielding replicates are likely to reflect restrictions to growth that are due to factors not considered in the LP model. In addition, weather data that were used as inputs to Kvifte's model, was collected from recording stations that are geographically close to the respective crop trial (in most cases less than 20 km), and are consistent with the timing of the experiment (Arnold, 1991).

To compare the predictions of Kvifte's (1987) simulation model (which assumes that crop yield is not restricted by soil moisture or nitrogen) with physical trial data (where yield may be restricted by these factors) the outputs of Kvifte's model are adjusted to reflect differences between the water holding capacity of soils, nitrogen status and year of harvest for each trial and a reference value. The method that was used to determine the influence of these factors involved performing a REML analysis on the collected trial data. The reference values are estimated at a level that is assumed not to limit crop growth. In the case of available water holding capacity, the reference value is taken as 110 mm which is the value assigned to the heaviest soil type in the LP model; the reference value for nitrogen is 275 kg per hectare; and the reference year, 1995, is the base year for the experiments reported in Chapter 9.

The variables that are included in the REML analysis are the available water holding capacity of the soil, the sum of nitrogen inputs to the crop, and trial year. The water holding capacity of the soils at the various experimental sites are assumed to equal the average of the respective soil association (MacDonald *pers. comm.*, 1995; McTaggart *pers. comm.*, 1995). Nitrogen inputs are calculated by summing the nitrogen that is derived from fertiliser, manure, atmospheric depositions (see Table 5-6), and net mineralisation (see Table 5-7). The results of the analysis are presented in Table 8-1.

Table 8-1. REML Analysis of Scottish Crop Trials.

Variables	Vining Peas	Winter Oilseed Rape	Spring Barley	Winter Barley	Winter Wheat
AWC	-39.53 (s.e. = 12.02)	-458 (s.e. = 184)	-321.6 (s.e. = 109.1)	21.55 (s.e. = 5.29)	113.1 (s.e. = 61.2)
AWC^2	n.s.	2.23 (s.e. = 0.88)	1.587 (s.e. = 0.54)	n.s.	-0.529 (s.e. = 0.32)
N	n.a.	-0.875 (s.e. = 0.42)	27.08 (s.e. = 1.73)	23.58 (s.e. = 1.68)	26.24 (s.e. = 2.99)
N^2	n.a.	n.s.	-0.064 (s.e = 0.007)	-0.0378 (s.e. = 0.004)	-0.0489 (s.e. = 0.007)
Year	n.s.	n.s.	54.57 (s.e. = 33.9)	n.s.	180.4 (s.e. = 54.3)

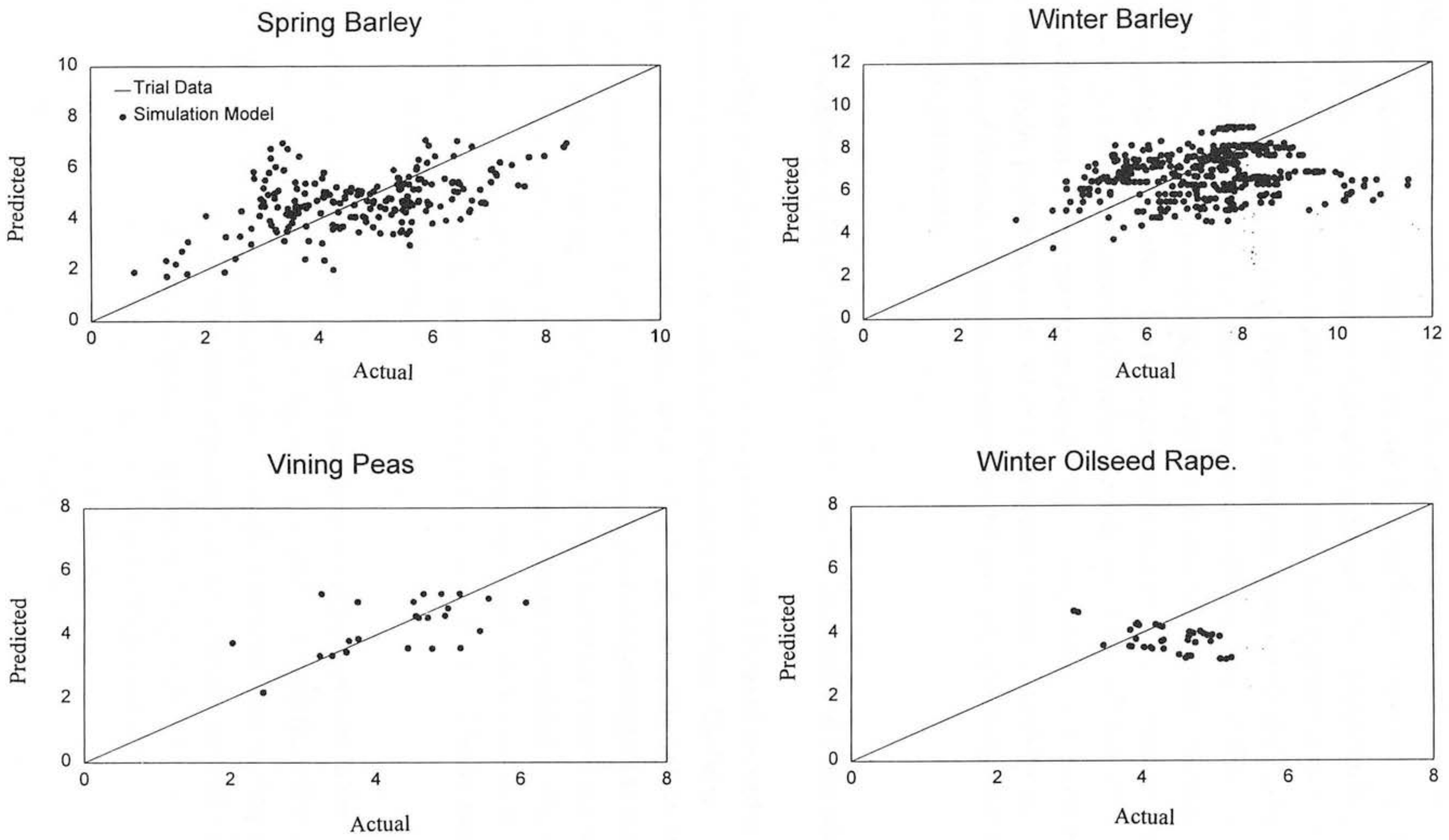
In the case of vining peas there is a significant relationship between soil water holding capacity and yield. The form of this relationship suggests a linear decline in yield of 39.5 kg per mm increase in soil AWC. Otherwise there are no significant relationships apparent in the data. To compare Kvifte's model predictions and the trial data, Kvifte's estimates are adjusted using the results of the REML analysis to account for differences between the soil AWC of the trials and the reference soil water holding capacity. The resulting estimates are compared with trial data in Figure 8-1. The average of the simulated estimates and the recorded trials is similar and prediction errors range between an under prediction of 1.58 tonnes per hectare and an over prediction of 2.02 tonnes per hectare. Although the number of data points in Figure 8-1 is relatively small, the distribution of these points indicates an acceptable level of prediction error.

For oilseed rape, the REML analysis suggests the presence of a quadratic relationship between soil water holding capacity and crop yield. For soil water holding capacities that are likely to occur in the field, the form of the relationship is for crop yields to decline with increasing soil water holding capacity. Also, a negative linear relationship is found between nitrogen application rates and crop yield. This result is contrary to expectations but may be due to increased rates of lodging that occur with higher rates of nitrogen use (Barton *pers. comm.*, 1995). As with vining peas, the yield of winter oilseed rape is estimated by adjusting the predictions of the Kvifte's model to reflect the results of the REML analysis (see Figure 8-1).

It can be seen that although average yields are predicted reasonably well, that variations in yield are poorly predicted, with yields over predicted at low yields and under predicted at high yields. Of the crops considered here, oilseed rape produced the least satisfactory agreement between estimated and historical yields. The prediction errors range between an over prediction of 1.63 tonnes per hectare and an under prediction of 2.01 tonnes per hectare. The average yield of winter oilseed rape is under predicted by 0.57 tonnes per hectare or 13 percent. The poor predictive performance that is achieved for oilseed rape suggests that systematic errors may be present in the analysis, or that factors which are important determinants of crop yield are not addressed. However, the results may simply reflect the high degree of variability of oilseed rape crops that are produced in Scotland. Hunter *pers. comm.*, (1995), suggested that the current climate in Scotland is marginal for the production of oilseed rape so that small changes in weather conditions may have a disproportionate effect on crop yields. Further difficulties associated with harvesting can produce large variations in the quantity of grain that is harvested from a crop (Barton *pers. comm.*, 1995). It is possible that a warming of the Scottish climate may result in oilseed rape yielding at higher and more consistent levels. However, given the available data it can not be stated that Kvifte's model will provide reliable estimates of oilseed rape yield for the climates considered in this study.

With respect to spring barley, the REML analysis indicates that yield responses to variations in available water holding capacity and nitrogen applications are quadratic in form. Further, that yields decline with increases in available water holding capacity and increase with applications of nitrogen. The trial year is positively related to yield and suggests that technological change has an impact on crop yield. The simulated yields are adjusted to reflect the results of the REML analysis (see Figure 8-1). Although there is a relatively wide spread of data points, with errors ranging from under predictions of 2.36 tonnes per hectare to over predictions of 3.60 tonnes per hectare, the distribution of these errors appears to be acceptable.

Figure 8-1. Comparison of Kvifte Model and Trial Data. Crop Yield (tonnes DM / hectare)



The last crop that is included in Figure 8-1 is winter barley. For this crop the REML analysis indicates a linear increase in yield with increasing soil water holding capacity. A quadratic relationship between nitrogen application rates and crop yield is also significant. At application rates that occur in practice, the relationship between nitrogen and yield is for winter barley yields to increase with application rate. As with other crops that are presented in Figure 8-1 simulated yields are adjusted using the results of the REML analysis to allow a comparison with trial data. In Figure 8-1, it can be seen that the range of prediction errors for winter barley trials are similar to those found for spring barley. The largest under prediction is 5.32 tonnes per hectare, and the largest over prediction is 2.35 tonnes per hectare. The prediction errors are greatest for yields above 9 tonnes per hectare. If these replicates are excluded then the largest under prediction is reduced to 3.2 tonnes per hectare, and differences in the average of the trials and the model are reduced from 0.675 tonnes per hectare to 0.32 tonnes per hectare.

8.2.2 Evaluation of the LP's Ability to Model Crop Responses to Nitrogen.

The ability of the linear equations that are present in the LP model to predict responses in crop growth to nitrogen are discussed in this section. The linear equations that represent winter wheat, winter oilseed rape, and spring and winter barley are compared with Scottish trial data. In the case of oilseed rape and barley, the same trials that are used to evaluate Kvifte's (1987) model are used to consider the influence of nitrogen on crop yield. The trials that are used to evaluate winter wheat are included in Appendix 8. The criteria for selecting winter wheat trials to be included in this study are the same as those used for oilseed rape and barley (see discussion in the preceding section).

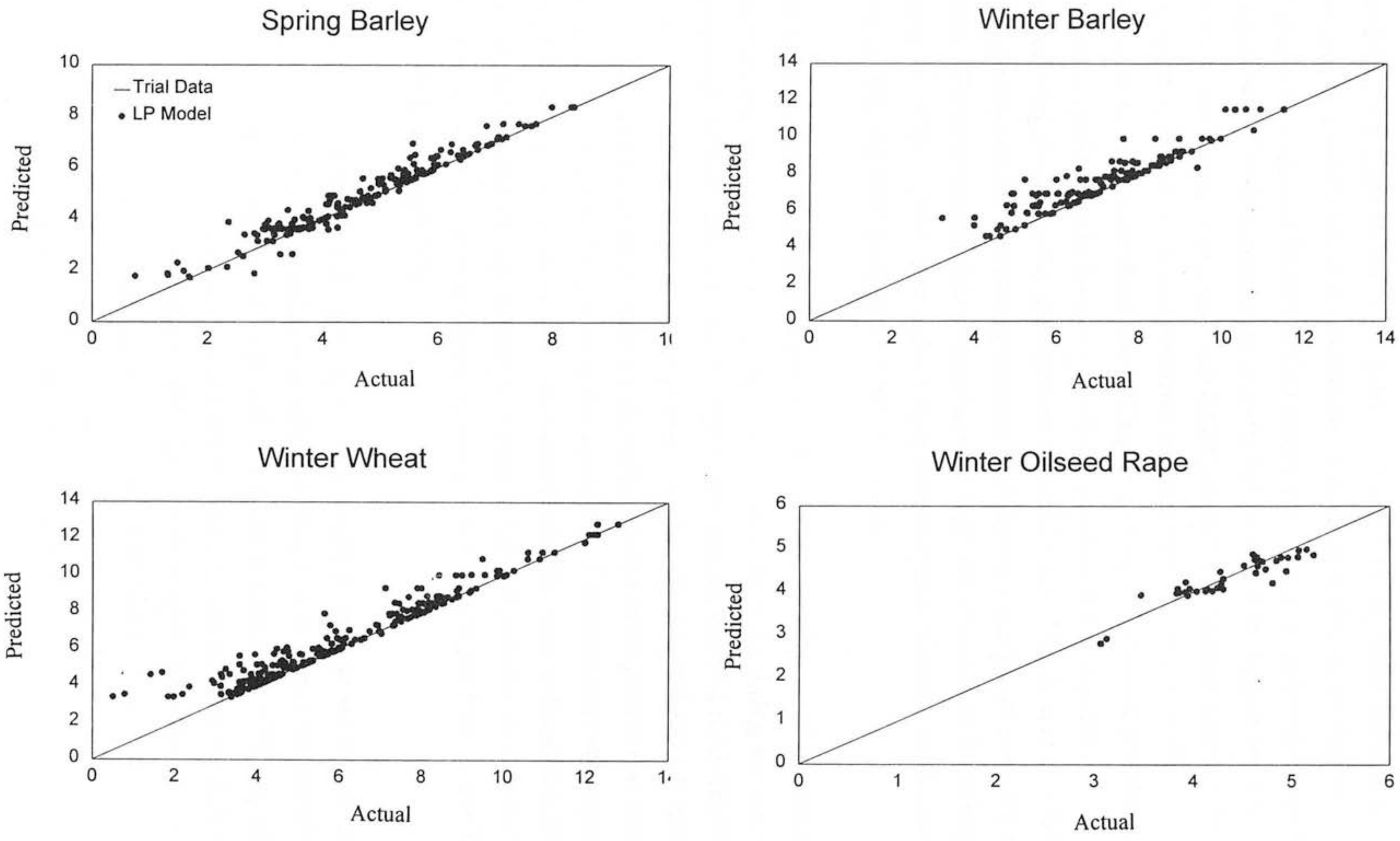
To compare the performance of the linear equations that are present in the LP crop models (that is Equations 5-1, 5-2, 5-14, 5-16, 5-17 and 5-18) with the collected trial data, the following assumptions are made. The highest yielding replicate from each trial is assumed to represent the potential yield of a crop grown in a particular year and location without nitrogen limitations. The potential growth profile is estimated for each trial, by assuming that in each period, the potential growth of a crop is proportional to simulated estimates of potential growth where the simulation estimates are calculated from inputs that are specified for each trial; that is sowing and harvesting dates, historical weather data (Arnold, 1991), and inputs of nitrogen.

The timing and amount of fertiliser nitrogen that is applied to the crops is taken from details relating to the respective trials. Assumptions relating to the amount of nitrogen that is derived from atmospheric deposition and soil mineralisation are taken from Table 5-6 and Table 5-7. In trials where the history of the field is known the amount of nitrogen that is transferred from a preceding crop is taken from Table 5-5. When the field history is not known the amount of nitrogen transferred from a preceding crop is estimated using a routine to minimise errors between the LP estimates of yield and trial yields, subject to restrictions that the transfer of nitrogen is the same for all of the treatments in a particular trial and that the amount that is transferred is between the maximum and minimum values included in Table 5-5.

The remaining parameters that are specified include the amount of nitrogen that is taken up by growing crops, and losses associated with leaching, denitrification and volatilisation. These parameters are taken from Table 5-8 and Table 5-10. The parameters relating to potential crop growth and nitrogen status are included in Equations 5-1 and 5-14. The estimates that are derived from these equations are compared with historical yields in Figure 8-2. It can be seen that a good level of agreement is found between the LP estimates of crop growth and the recorded trial yields.

For winter wheat, prediction errors between the linear equations and trial data range from under predicting yield by 0.2 tonnes per hectare to over predicting yield by 3.16 tonnes per hectare. This compares with differences measured in the field of up to 6.25 tonnes per hectare between treatments in the same trial. For oilseed rape, a similar comparison shows prediction errors ranging between -0.60 tonnes per hectare and +0.45 tonnes per hectare; and compares with differences of up to 0.96 tonnes per hectare for different treatments in the same trial. For spring barley, prediction errors range between -0.94 and +1.51 tonnes per hectare. For this crop, between treatment differences in the same trial are up to 4.97 tonnes per hectare. For winter barley, prediction errors range between -1.1 and +2.46 tonnes per hectare, while yield differences of up to 3.83 tonnes per hectare are recorded for treatments in the same trial. For all of the crops, except oilseed rape, there is a tendency for yields to be over predicted, however, the size of these errors is not large. The results suggest that the LP model of the uptake and cycling of nitrogen is appropriate with respect to this study.

Figure 8-2. Comparison of Linear Programming Model and Trial Data. Crop Yield (tonnes DM / hectare)



8.2.3 Evaluation of LP Estimates of Pasture Growth.

The ability of Equations 5-3, 5-14, 5-16, 5-17 and 5-18 to predict changes in pasture growth are considered in this section. A number of time series that were established with Topp and Doyle's (1994) model, are compared with predictions from these equations. The time series data consider the growth of both grass and grass / clover for various sites, years, soil water holding capacities, nitrogen application rates and animal stocking rates. The experiments and assumptions relating to the simulation of these trials are discussed in Chapter 3 of Topp and Doyle (1994). In one of these experiments the influence of nitrogen on the growth of grass is considered using scenarios that are based on the GM20 trial (Morrison *et al*, 1980). This experiment involved measuring the yield of silage for a number of sites, soil types and years. The trials selected for comparison are High Mowthorpe and Seale Hayne for the years 1970 to 1973. For each of these sites and years, nitrogen application rates of 0, 300, and 600 kg per hectare are considered.

The following assumptions are introduced to allow the predictions of the linear equation set and the simulation model to be compared. First, the timing and amounts of nitrogen application, and amount of silage that is cut, are assumed to be the same as those estimated by Topp and Doyle (1994). Further, the potential growth rate of pasture is taken to equal the respective maximum rate of pasture growth that occurred for each month, year and site (see a2 in Equation 5-3). The parameters relating to pasture loss (see a5 in Equation 5-3) are assumed to be the same as those included in Table 5-4; parameters relating to nitrogen turnover and losses in soil are assumed to be the same as those for current climatic conditions (climate '0') at Paisley (see Table 5-6, Table 5-7, and Table 5-8.

The estimates relating to the quantity of leaf material in the field are derived from the linear equation set and simulation models and compared in Figure 8-3 and Figure 8-4. At High Mowthorpe, it can be seen that with the exception of 1970, that good agreement between the predictions of the linear equations and simulation models is achieved. Between the years 1971 to 1973 the maximum under prediction of leaf in any month is 476 kg per hectare. In the same period the maximum over prediction is 673 kg per hectare. These compare with prediction errors for the zero nitrogen application rate in 1970 that range from -687 kg per hectare to +1043 kg per hectare. Although there

Figure 8-3. Comparison of Linear Programming and Simulation Models. Quantity of Leaf (kg DM / ha). Site = High Mowthorpe, Sward = Grass.

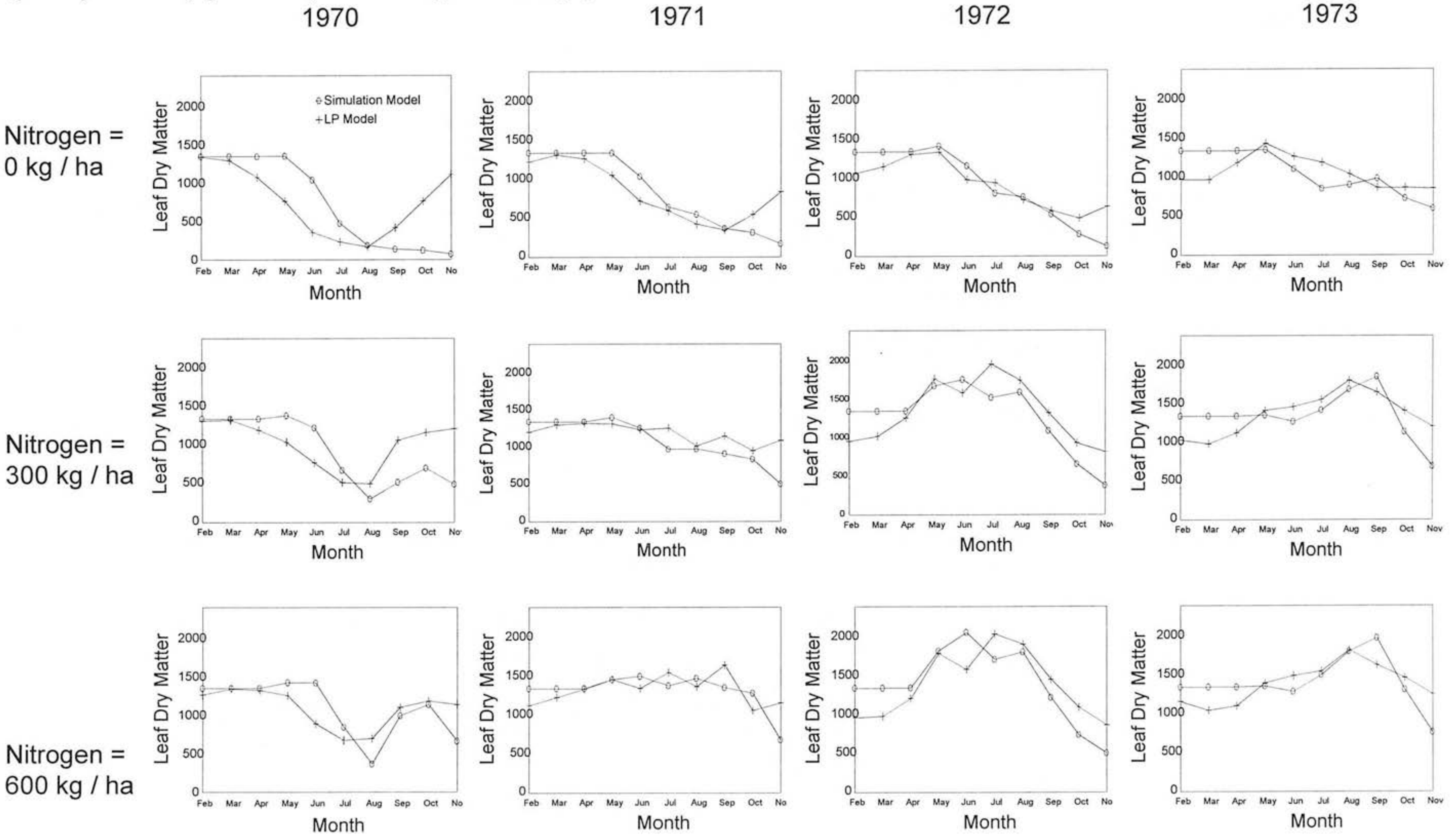
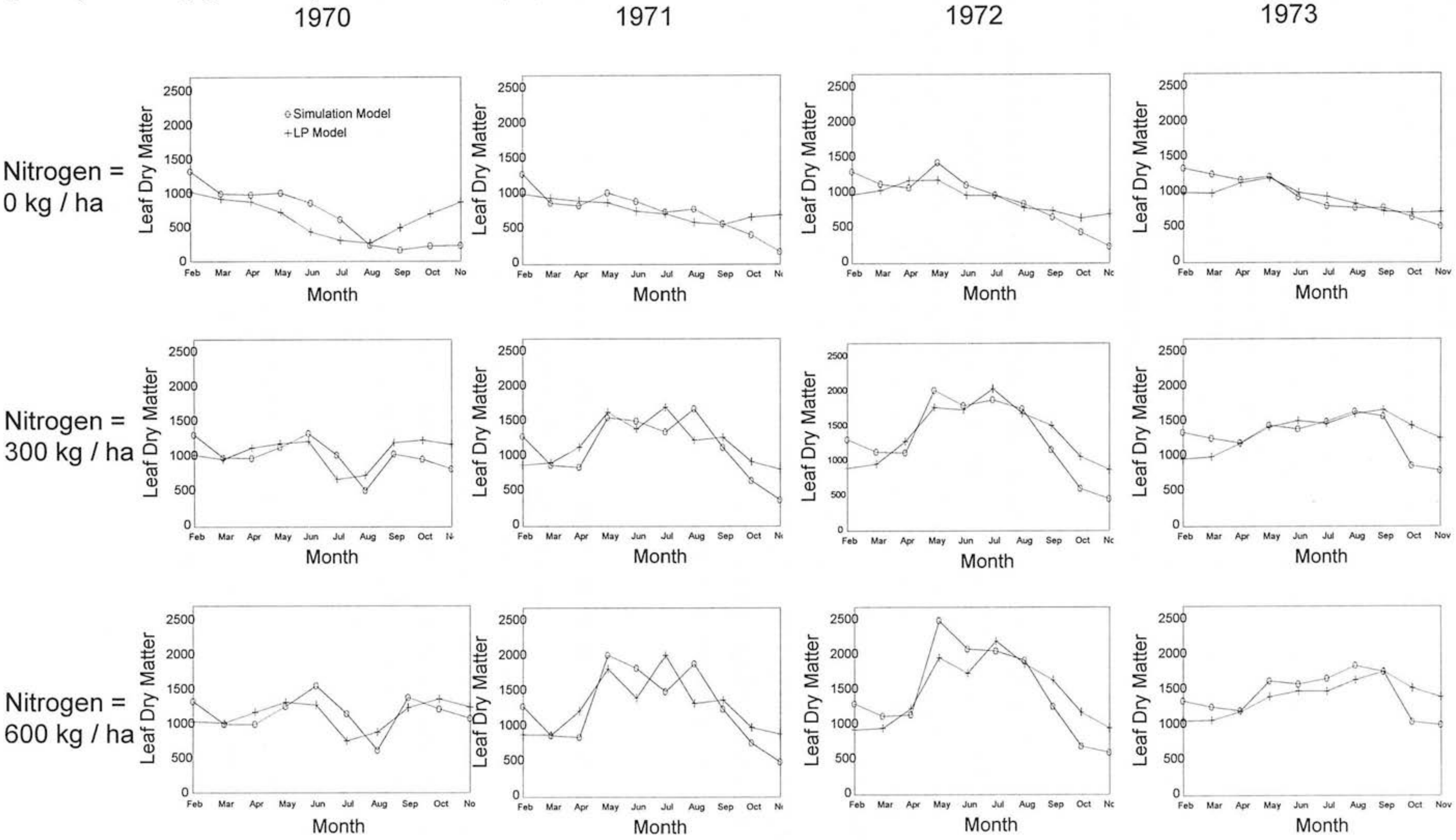


Figure 8-4. Comparison of Linear Programming and Simulation Models. Quantity of Leaf (kg DM / ha). Site = Seale Hayne, Sward = Grass.



are divergence's between the LP and simulation estimates in the amount of leaf material in the sward, the mean of these differences is small.

The errors associated with predicting the average amount of material present in the sward range from -1.4 to +5.2 percent. At Seale Hayne, a good level of agreement is achieved for all of the years and nitrogen application rates that are considered. The prediction errors at this site range from -560 to +638 kg of leaf per hectare. Predictions relating to the average amount of leaf material in the sward also appear to be acceptable and range from under predictions of 2.5 percent to over predictions of 5.7 percent.

The grass / clover linear equations (that is Equations 5-3, 5-14, 5-16, 5-17 and 5-18) are evaluated against time series data produced by Topp and Doyle's model that are based on data from the GM23 trial that was supplied to Topp and Doyle by Gilbey (*pers. comm.*, 1994). The GM23 trial was conducted at three sites (High Mowthorpe, Liscombe, and Rosemaund) between the years 1978 and 1980. The effect of nitrogen application rates on grass / clover swards is considered in the experiment. The nitrogen treatment levels were for 0 and 200 kg's of nitrogen to be applied to the High Mowthorpe and the Liscombe sites. At Rosemaund, nitrogen was applied at rates of 0 and 300 kg per hectare in 1978 and 1979; and in 1980 nitrogen was applied at 0 and 200 kg per hectare.

The comparison of the linear equation set and the simulation models involved similar assumptions to those used to evaluate the linear equation set for grass. It is assumed that the potential growth of grass / clover equals the maximum growth rate recorded for the respective month, year and site. The parameters associated with leaf losses that are due to death and decay are taken from Table 5-4, while parameters that determine the nitrogen status in soil are taken from Table 5-6, Table 5-7, Table 5-8, Table 5-10 and Table 5-9.

At High Mowthorpe, prediction errors (between the linear equation set and the simulation model of Topp and Doyle) that relate to the monthly totals of leaf range from -319 to +491 kg per hectare (see Figure 8-5). The quantity of leaf in the sward, when averaged for the year, is over predicted by the linear equation set by 0.5 to 9.2 percent. At Liscombe, predictions by the linear equation set of the quantity of leaf in the sward ranged between under predictions of 264 kg per hectare to over predictions of 501 kg per hectare (see Figure 8-6). The annual average of the prediction errors at

Figure 8-5. Comparison of Linear Programming and Simulation Models.
Quantity of Leaf (kg DM / ha). Site = High Mowthorpe, Sward = Grass / Clover.

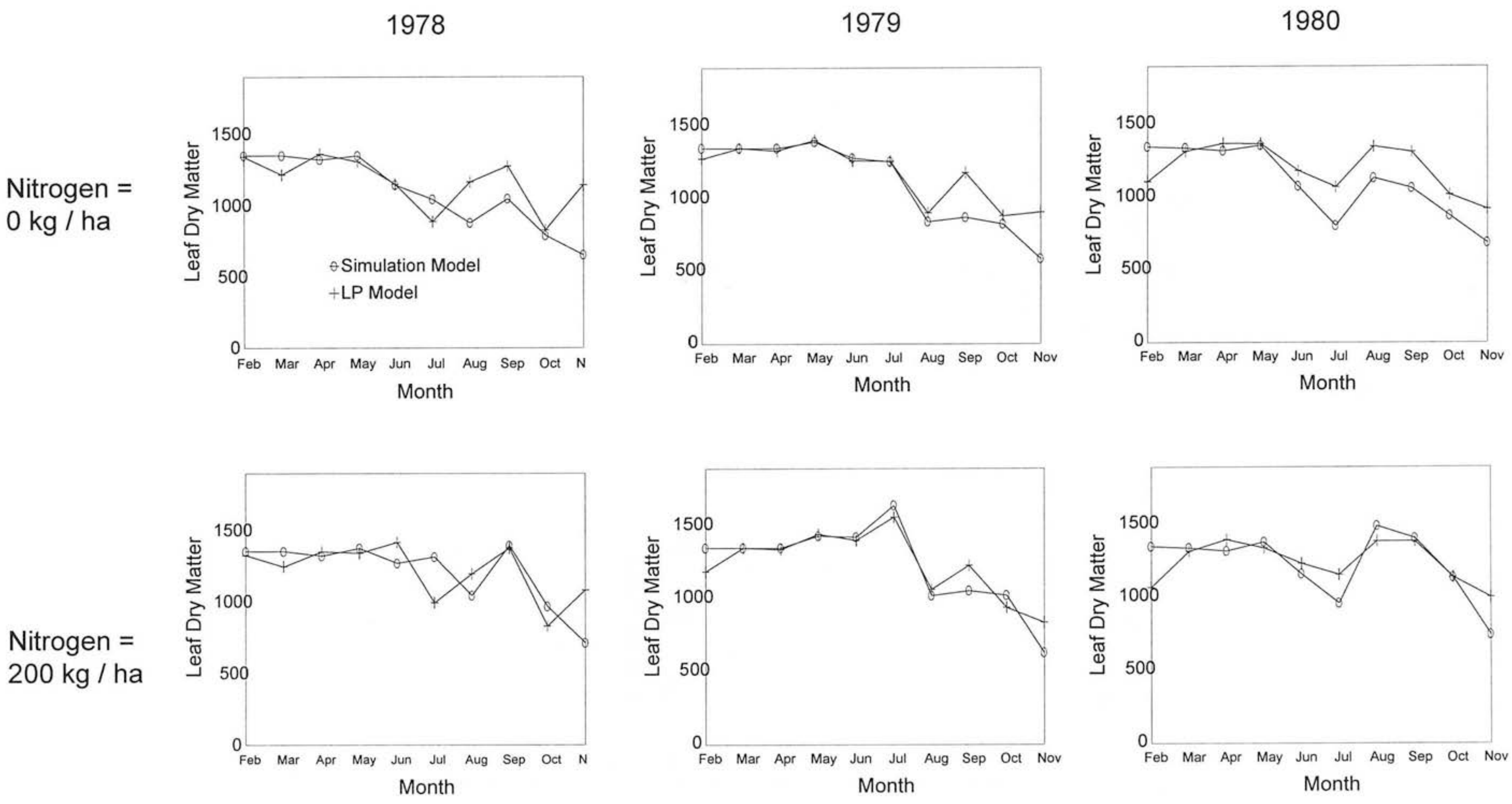


Figure 8-6. Comparison of Linear Programming and Simulation Models.
Quantity of Leaf (kg DM / ha). Site = Liscombe, Sward = Grass / Clover.

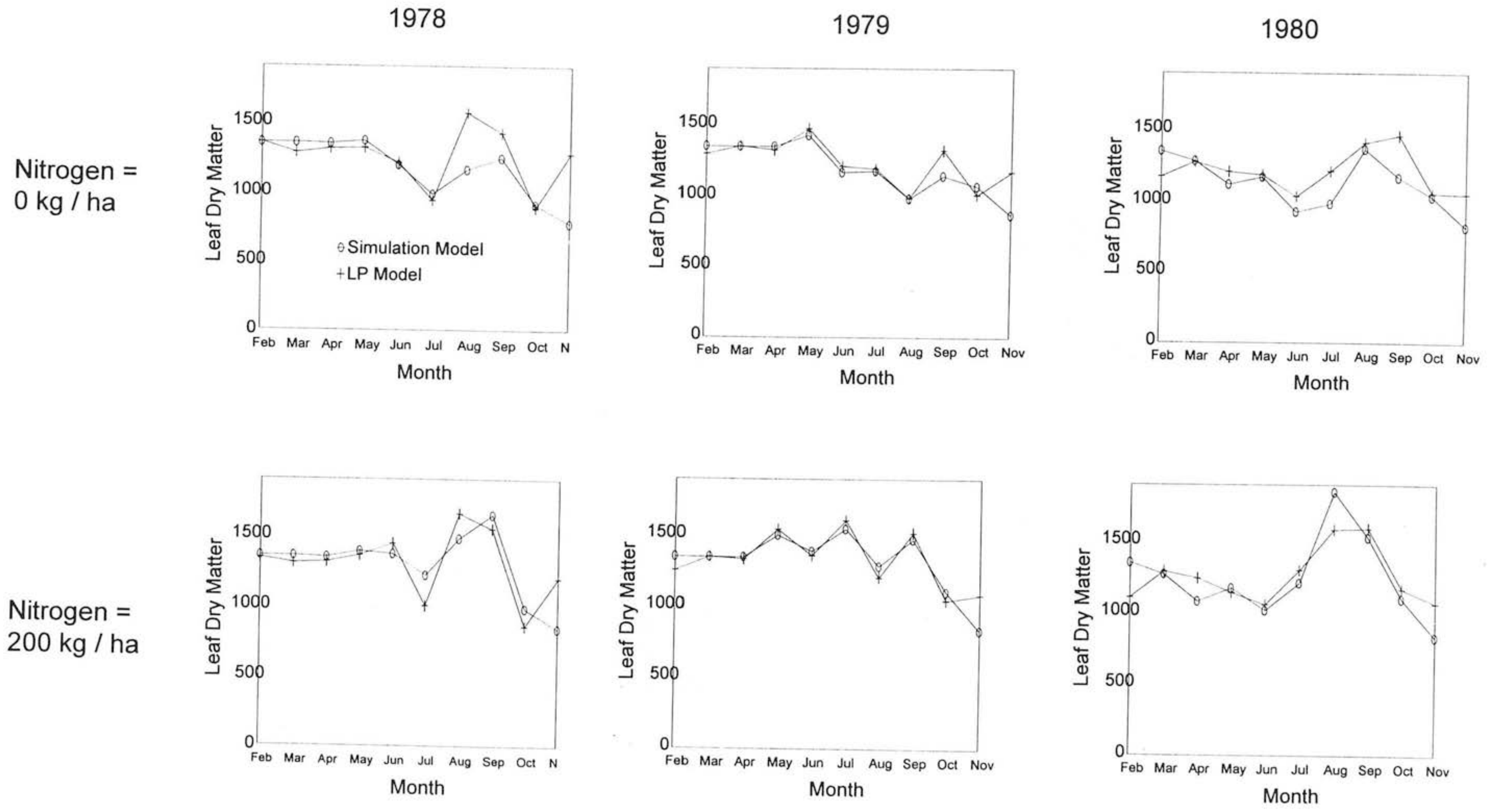
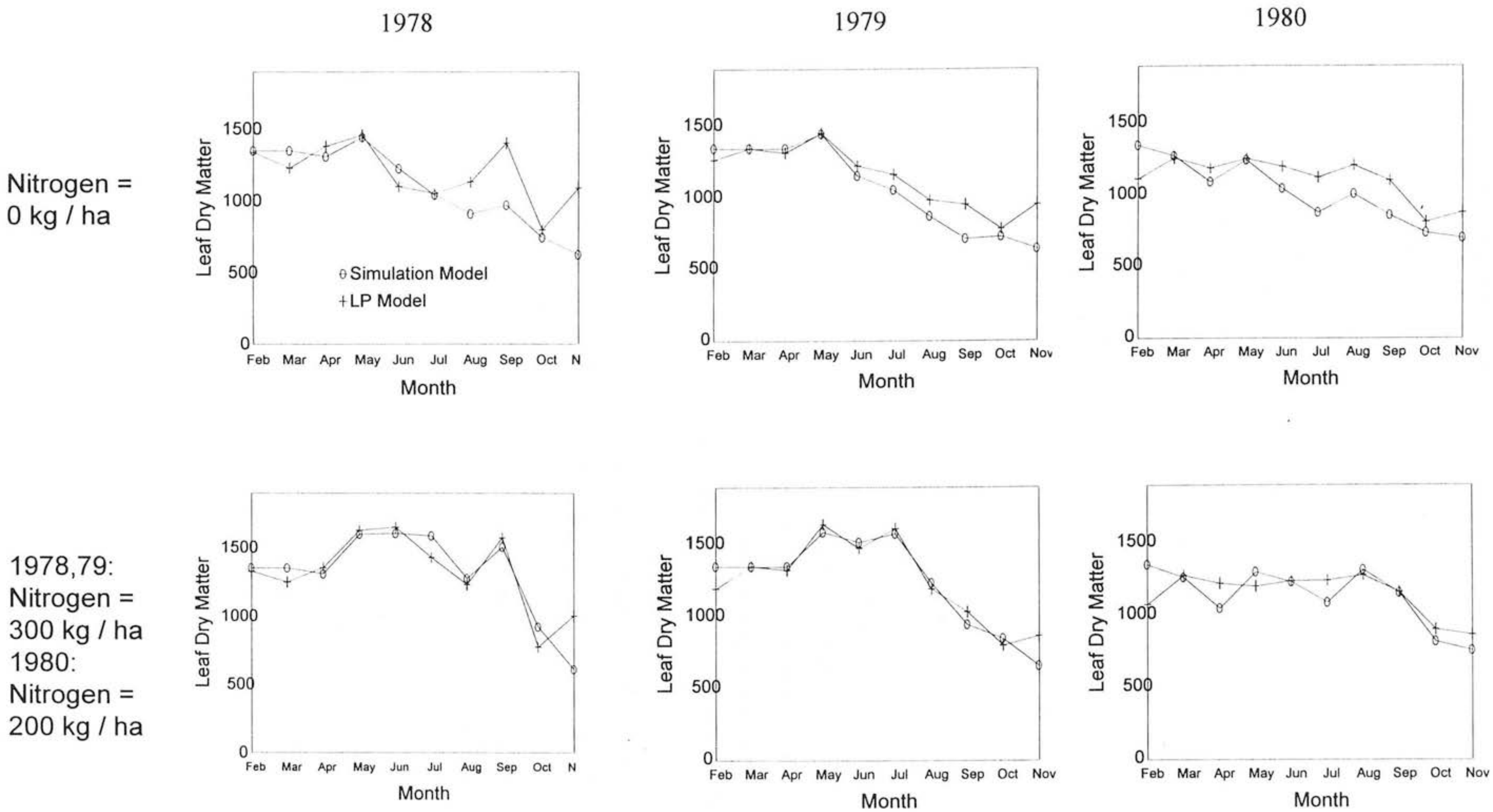


Figure 8-7. Comparison of Linear Programming and Simulation Models.
Quantity of Leaf (kg DM / ha). Site = Rosemaund, Sward = Grass / Clover.



Liscombe range from 0.3 to 7.6 percent. These compare with Rosemaund (see Figure 8-7), where prediction errors range between -275 and +468 kg per hectare. The annual prediction errors at Rosemaund are similar to the other sites with errors between 0.6 and 9.4 percent.

For all of the sites and for both grass and grass / clover, there are no obvious patterns to the prediction errors and the level of errors that occurred on fields receiving high rates of nitrogen application are similar to those that did not receive any nitrogen. Further, there does not appear to be a tendency for prediction errors to accumulate between modelled periods. The error levels are similar for the various months, and in general are no larger at the end of the modelled series rather than in earlier periods.

8.3 Animal Model.

It is assumed that the scenarios produced by Topp and Doyle's (1994) simulation models are valid representations of changes in productivity for the conditions relevant to this study. The simulation models of animal production systems were tested extensively for British conditions by Topp and Doyle and are adopted in this study without further testing. The evaluation of the linear equations that are present in the LP model (that is Equations 6-1 to 6-10) involved comparing the estimates of liveweight change that are derived from the linear equation set with estimates from the models of Topp and Doyle (1994). In the case of dairy animals, the level of milk production is also considered. The results of these comparisons are presented in Figure 8-8 to Figure 8-10. The data presented for beef, dairy and sheep demonstrate the ability of the linear equations to describe the changes in productivity that occur with differing climates, regions, years, pasture types and stocking rates.

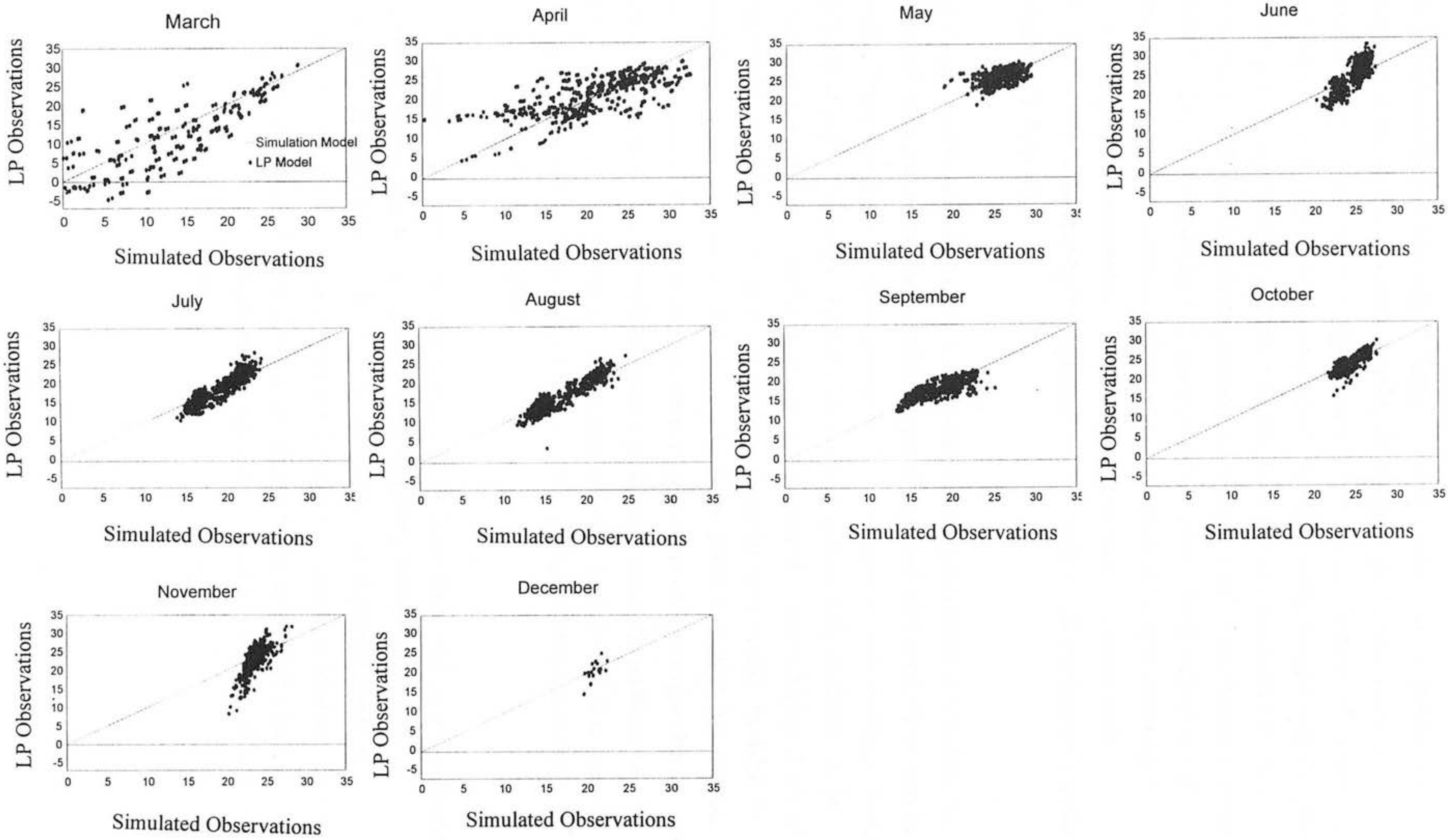
The scenarios that are considered include 8640 years of simulated time, that is 3 animal types * 4 regions * 3 climates * 2 pasture types * 4 soil types * 3 stocking rates * 10 years of weather. The estimates of liveweight change and monthly milk production that are presented in Figure 8-8 to Figure 8-10 incorporate the influence of changes in pasture availability on animal intake. In the linear model, pasture availability is calculated from the mean of the 12 paddocks that are represented by Topp and Doyle (1994). Animal intake is determined, therefore, as a function of pasture availability and the amount of concentrates that are fed to animals.

As discussed in Section 6.1, the parameters that relate to beef are estimated from time series data that involve cattle that are purchased in January at 6 months of age. The fattening system involves holding animals for approximately 12 months before selling. At the time of purchase, animal liveweights are set to equal 180 kg (Topp *pers. comm.,* 1994). Further, it is assumed that animals are fed concentrates, during the time that animals are housed, at the same rates as those specified in Topp and Doyle's scenarios.

In Figure 8-8, the predictions of liveweight change that are derived from the linear equations are compared with Topp and Doyle's estimates for the period March until December. It can be seen that in general good agreement is achieved between the linear model of liveweight change and the estimates established by Topp and Doyle's simulation models. The least accurate predictions from the linear model tend to be in March and April when errors are evident at low growth rates. In March the maximum under and over-predictions of liveweight are 13.3 and 16.3 kg per head per month, and correspond to an average under prediction of 12.2 percent. In April the maximum under and over predictions of growth are 11.5 and 15.0 kg per head per month, and the average difference between the simulation and the linear models is 0.4 percent. In the remaining months, the prediction errors of the LP model range between an under prediction of 12.1 kg in November and an over prediction of 6.5 kg per head per month in June. In all of these months, the average of the prediction errors is less than 2 percent of the simulated estimates.

The predictions of liveweight change and milk production of dairy animals are compared with output from Topp and Doyle's simulation model in Figure 8-9. The predictions of the linear and simulation models are compared for the months June to November. The predictions of liveweight change and milk production tended to be most accurate in the months June and July. In these months, the prediction errors associated with liveweight change range between -1.9 and +3.1 kg per month, and for milk production between -25.3 and +13.3 kg per month. In these months the mean of the linear model estimates of liveweight change and milk production are less than 2 percent different to the estimates derived from the simulation model.

Figure 8-8. Comparison of Linear Programming and Simulation Models. Beef Animals - Liveweight Change (kg / month)

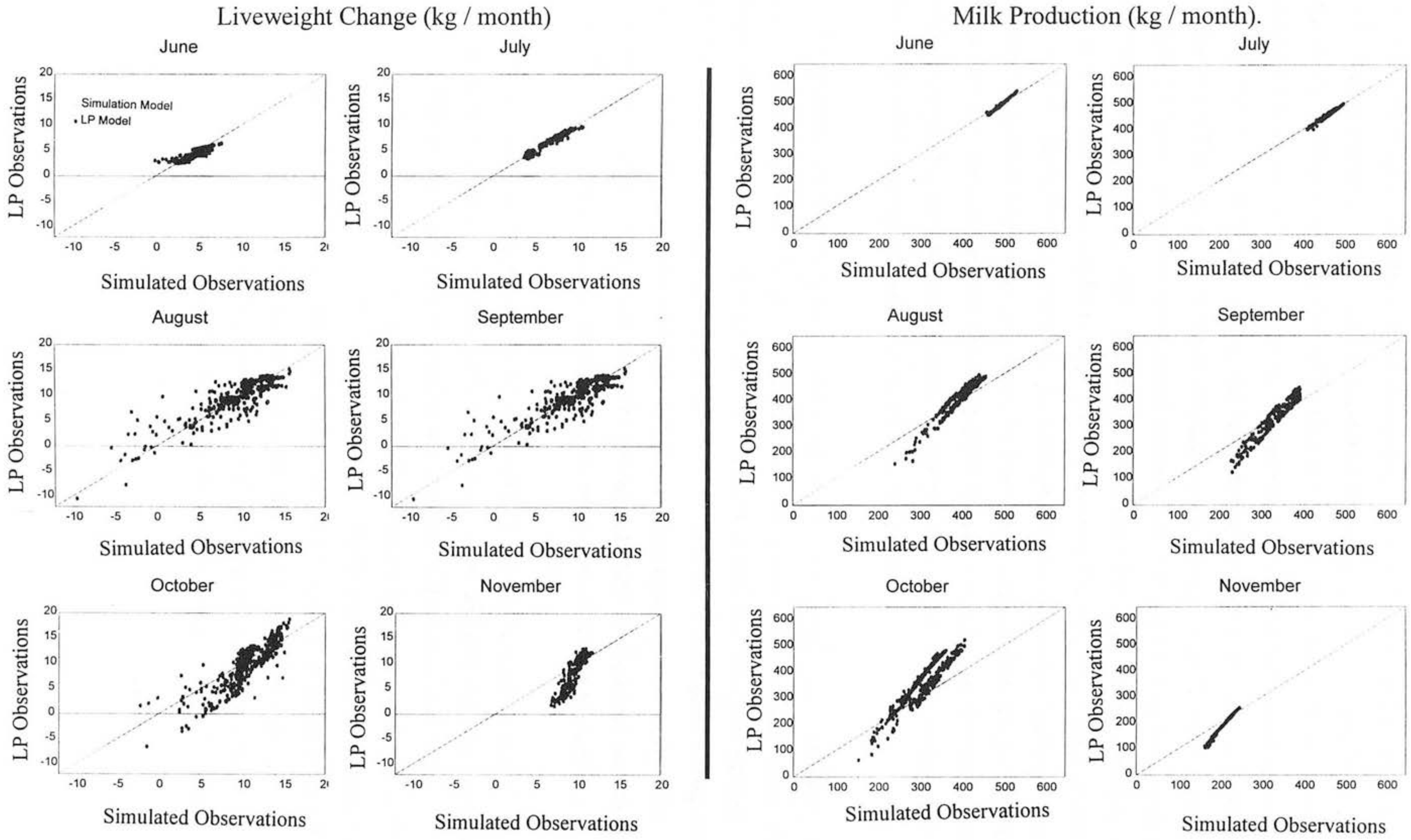


In the remaining months that animals are grazing pasture (August to November), prediction errors for both liveweight change and milk production are greater than those earlier in the season. In these months, the range of prediction errors for liveweight change is -8.3 and +9.6 kg per month; for milk production errors between -119.7 and +126.6 kg per month are recorded. For the months August until October, the average liveweight change predicted by the linear model is between 1.2 and 3.6 percent greater than the simulated estimates. In contrast, liveweight change is under predicted by the linear model by 11.3 percent in November. With respect to milk production, the linear model over estimated milk production by approximately 5 percent in August and September. This compares with October where milk production is over estimated by 24.6 percent. In November milk production is under-estimated by 7.4 percent.

Although, a relatively large error is recorded for milk production in October, the majority of prediction errors for both liveweight change and milk production tend to be small. Of greater concern, is the presence of a systematic error in the linear models predictions of milk production. At low levels of milk production, the linear model tends to under predict the quantity of milk that is produced, while at higher levels of production the model over predicts production. A similar error is also recorded for liveweight change in November. The reason for these errors is unclear, but may be related to the method used to determine the energy content of liveweight change. An informal test of the model showed that model predictions are quite sensitive to changes in the parameters kf and a25 (see Equation 6-3). In this study it is assumed that the agreement between the linear and simulation models is adequate for the LP model to fulfil its intended purpose.

In Figure 8-10 the linear models predictions of the liveweight change of sheep and lambs are compared (for the months May until October), with output from the simulation models of Topp and Doyle. For both lambs and sheep the range of prediction errors in months prior to May are similar to the errors in May and the level of errors in the months following October are similar to the errors that occur in October. For both the sheep and lamb models there is a tendency for prediction errors to increase in later months.

Figure 8-9. Comparison of Linear Programming and Simulation Models. Dairy Animals.

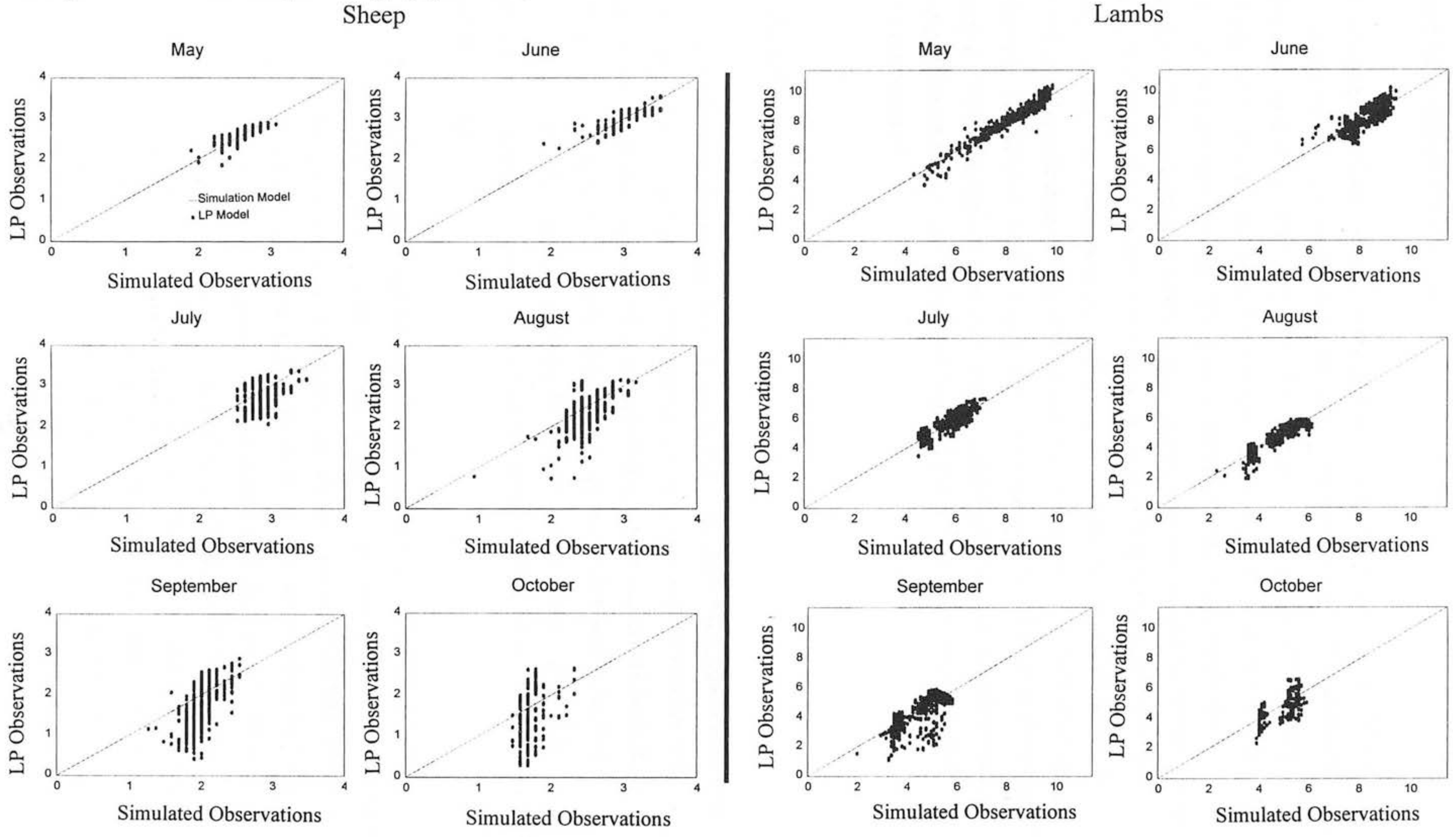


In May and June, the prediction errors from the sheep linear model ranged between -0.5 and +0.5 kg per month, and for the lamb linear model, errors of between -1.9 and +1.4 kg per month are observed. In these months, the average of the predictions from the sheep and lamb linear models is less than 0.5 percent different to the mean of the estimates from the simulation models. The errors recorded for July and August are greater than those in May and June, but less than the errors that occur in the months at the end of the season. In July and August, errors relating to predictions of live weight change by the sheep linear model are between -1.6 and +0.7 kg per month, and for the lamb linear model errors are between -1.6 and +0.9 kg per month. In July and August, the lamb linear model is slightly more accurate than the sheep linear model. For both the sheep and lamb models, the average difference between the linear and simulation models is less than 2 percent. In September and October, the prediction errors for the sheep models are similar to those in earlier months. With respect to the lamb linear model, the prediction errors are greater in September and October than in earlier months ranging between -3.0 to +1.4 kg per month.

The purpose of evaluating the animal linear models is to demonstrate the ability of the models to reproduce the predictions of Topp and Doyle's simulation models. The linear model performed well in this respect. It is concluded that the linear models provide an acceptable description of animal performance for the range of management variables and environmental conditions that are relevant to the current study. The results of the evaluation suggests that the approach of using simple linear models to reproduce the predictions of relatively complex simulation models is appropriate.

While the linear model provided reasonable predictions in the context of the current study the range of conditions that the linear model will give realistic estimates for is uncertain. Also, the parameters that are included in the linear models are specific to the management variables selected as constants by Topp and Doyle (1994). In the case of the beef model, the model parameters would need to be re-estimated if factors such as the age, sex, weight or breed of animals that are purchased is varied, or if animals are held on the farm for longer than the 12 month period that is considered. Also, parameters for the dairy and sheep systems are specific to the assumed age structure of the herd or flock and the assumed date of animal conception and subsequent commencement of lactation.

Figure 8-10. Comparison of Linear Programming and Simulation Models.
Sheep and Lamb Liveweight Change (kg / month)



9. BASE RUN AND SIMULATIONS.

This chapter is in four sections. In the first section the outputs of some preliminary runs with the model are considered. In the second section a sensitivity analysis of relative changes in the productivity of machine harvested crops (potatoes, barley, vining peas, oilseed rape and wheat) and crops harvested by animals (grass, grass / clover and swedes) is presented. These runs were performed to compare the sensitivity of livestock farming systems with systems that are dependent on the sale of crop produce. The third section involves an analysis of long term adjustments in farming systems with changes in climate. In these runs the purchase and selling of land and also the influence of relative changes in the numbers of capital livestock is considered. The purpose of this experiment is to determine the effect that differences in relative profitability (given alternate climatic conditions) have on the relationships between different farm types. In the final section a summary of the experimental results is presented.

9.1 Base Runs.

In the model runs that are reported in this section, the right hand side coefficients that relate to the area of land, financial status, casual labour and the numbers of capital livestock that are associated with each farm type and region are included at 1995 levels (see Appendix 3). Further, there is no provision for land or capital livestock to be sold between the different farm types. Otherwise the model is relatively unconstrained particularly with regard to the amount of land that is allocated to different crops.

The outputs of the model run are based on the climate '0' scenarios and are compared with census data in Table 9-1 and Table 9-2. In these tables the numbers of livestock and the areas planted to different crops in Scotland are reported. It can be seen that the model is better at estimating the numbers of livestock than the areas of crops. With regard to livestock the prediction errors in all cases are less than 1 percent. To an extent this result was expected as livestock numbers are limited by (amongst other constraints) the number of capital or breeding livestock. In contrast crops are not subject to any simple upper limit, rather they are constrained by relatively general rotational constraints and by requirements for factors such as machinery and labour.

From Table 9-2 it can be seen that grass and grass / clover areas are over-predicted by approximately 37 percent and with the exception of peas the other crops are under-predicted by the model. In the case of peas the model over-predicts the planted area by approximately 175 percent. It should be noted, however, that peas are a relatively minor crop that only account for approximately 0.25 percent of the total arable area. Of greater concern are the prediction errors associated with cereal crops which range between an under-prediction of 71 percent for winter barley and an under-prediction of 98 percent for wheat crops. In the case of potatoes and oilseed rape the model estimates are 59 and 75 percent less than were actually planted. Although the predictions of the individual components of the model are generally acceptable, the errors associated with the aggregate behaviour of the model is less satisfactory.

Table 9-1. Comparison of 1995 Census Data[138] and LP Model Predictions. Animal Numbers (000's)

	1995 Census Data	LP Model Predictions
Beef Animals	468	467
Dairy Cows	243	244
Breeding Ewes	4585	4585

Table 9-2. Comparison of 1995 Census Data and LP Model Predictions. Crop Areas (hectares, 000's)

	1995 Census Data	LP Model Predictions
Grass and Grass / Clover	1065	1462
Spring Barley	270	42
Winter Barley	67	19
Wheat	111	2
Potatoes	27	11
Peas	4	11
Oilseed Rape	45	11
Total	1591	1560

There are a number of reasons that may have caused these errors. Firstly, the poor predictions may be related to the method of restricting the soil types that can be planted to crops that produce human feedstuffs (see Section 5.2.1). This may have contributed to the under-predictions of the model with regard to crops such as milling

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[138] Source: SOAEFD (1997).

wheat, malting barley, oilseed rape and potatoes. Given the relative profitability of these crops this suggests that an insufficient amount of land has been allocated for the production of these crops. However, it should be noted that the model also under-predicts the areas of feed barley and feed wheat and at the same time a small amount of land is not utilised on 'cropping' farms.

A second reason is that the method that is used to establish the farm typology involved selecting activities that contribute more than 20 percent of the farms income (see Section 3.3). This was done to simplify the analysis but may have restricted the area of land that can be planted to arable crops. This is because farms that grow small areas of crops but which are predominately livestock operations (in which case crops are not represented in the model), are relatively common in Scotland.

Another reason for the poor predictions of crop areas may be related to the fact that some of the policy instruments that are associated with the Common Agricultural Policy (CAP) are not explicitly represented in the model. The CAP has a significant influence on the structure of the agricultural industry (Thomson, 1987) and although many of the input and output prices (including direct payments for each hectare of a crop) that are included in the model reflect the presence of the CAP, the absence of certain policy instruments may have altered the relative profitability of different crops. While it would have been relatively straightforward to include a more detailed representation of some of the policy instruments in the model (such as restricting the amounts of payments that can be made), the wider issue of modelling the CAP is not a trivial exercise.

Further, at the time that the model was being developed, the CAP was undergoing a period of considerable reform. The base year, 1995, was therefore a transitional year and the policy instruments that were in place at this time are unlikely to be operating over the time frame that climatic change, of the magnitude that is modelled here is likely to occur. Rather, effort was directed towards representing variations that will be of consequence for the foreseeable future, that is the management and productivity of crop and animal systems. To the extent that the model meets this objective the model should be able to identify the types and directions of change that farmers are likely to implement. In this respect the results of the evaluations that are reported earlier in this chapter suggest that the model is acceptable. However, clearly if the model is used as part of a future study it would be desirable to improve the national level predictions of the model.

In the remainder of this section the outputs of some base runs with the model are considered for the climate scenarios '0', '1' and '2' (see Chapter 2). The model run that involves the climate '0' scenario is identical to the run that is discussed above. The runs that involve the climate change scenarios (climates '1' and '2') demonstrate some of the adjustments that farmers are likely to implement as climatic conditions evolve. The reason for performing these runs was to establish a basis for comparisons with the experiments that are reported in Sections 9.2 and 9.3. The model outputs that are considered principally relate to changes in the areas and productivity of crops, numbers of livestock, labour requirements and the financial situation of different farm types and regions.

As in the above LP model run, the right hand side coefficients that relate to the area of land, the initial cash position and repayments of fixed debts, casual labour and the maximum number of capital livestock that are associated with each farm type and region are maintained at 1995 levels (see Appendix 3). Also, land and capital livestock may not be sold between the different farm types. The results should therefore reflect the types of short term adjustments that farmers make to their farm plans. These adjustments include actions such as altering the mix of crops that are planted, the timing of crop sowing, applications of pesticides, fertiliser and farm yard manure, the method of crop residue disposal, the machinery and labour that are selected to perform these operations, the feeding of livestock and the marketing of crop and livestock products.

9.1.1 Animal Numbers.

In Table 9-3 it can be seen that the estimates of beef and dairy numbers are similar for each of the climatic scenarios. The predictions equate to approximately 0.47 m beef cattle and 0.24 m dairy animals in Scotland. For both of these livestock types the output of animal products (meat and milk) are similar for all the climatic scenarios. It should be noted that the numbers of beef and dairy cattle correspond to the limits on the maximum number of livestock. However, the situation for sheep is somewhat different.

In the climate '0' scenario there are approximately 4.59 m breeding ewes in Scotland, but for climate '1' there is a decline of approximately 17 percent to 3.82 m.

Similarly, between climates '0' and '2' there is a fall in sheep numbers of approximately 19 percent. With respect to climate '0' the number of ewes is limited by constraints that relate to the maximum number of livestock. This compares with climates '1' and '2' where (excepting the climate '1' scenario at Mylnefield) the numbers of ewes are not restricted by limits on breeding ewe numbers. The main reason for the fall in sheep numbers with changes in climate is related to the decline in pasture growth in autumn (see Section 5.3.1).

Table 9-3. Results of Base Runs. Animal Numbers (000's)

Region	Animal	Climate '0'	Climate '1'	Climate '2'
Kinloss	Beef	126	126	126
	Dairy	33	33	33
	Sheep	980	663	678
Mylnefield	Beef	109	109	109
	Dairy	19	19	19
	Sheep	884	884	759
Paisley	Beef	166	166	166
	Dairy	180	180	180
	Sheep	1985	1555	1726
Wick	Beef	66	66	66
	Dairy	12	12	12
	Sheep	736	717	561
Scotland	Beef	467	467	467
	Dairy	244	244	244
	Sheep	4585	3819	3724

9.1.2 Area and Yield of Crops.

The crop areas for Scotland are estimated from the outputs of the base runs and are presented in Table 9-4. For data that relates to regional crop areas see Appendix 11-1. In the case of grass, there is an increase in the national area from approximately 92,100 hectares for climate '0' to 199,900 hectares for climate '1' and 194,500 hectares for climate '2'. These correspond to changes of +117 and +111 percent, respectively. In comparison the area of grass / clover swards declines from 1,369,900 hectares for climate '0' to 1,159,900 hectares for climate '1' and 1,146,100 hectares for climate '2'. In percentage terms the changes in the area of grass / clover are approximately -15 and -16 percent. The increases in the area of grass tend to substitute for decreases in grass / clover but the net effect of climatic change is for the area of forage to decline by between 7 and 8 percent.

With respect to the cereal crops there tend to be declines in the national area with a change in climate. In the case of spring barley the model predictions suggest that 42,200 hectares are planted under current climatic conditions. This compares with 41,400 hectares for climate '1' and 18,800 hectares for climate '2'. There is little difference between the estimates for climates '0' and '1' but between climates '0' and '2' the change in area is approximately -55 percent. In comparison, the areas of winter barley are 19,100, 12,600 and 7,400 hectares for climates '0', '1' and '2', respectively. The model estimates for winter wheat are 2,500 hectares for climate '0', 200 hectares for climate '1' and 1,700 hectares for climate '2'.

The areas of potatoes, peas and oilseed rape appear to be less affected by changes in climate. For the climate '0' scenario there is approximately 11,400 hectares of potatoes. This compares with 11,600 hectares for climate '1' and 13,100 hectares for climate '2'. In contrast there is a small reduction in the national area of vining peas from 11,900 hectares for climate '0' to 11,000 hectares for climate '1' and 11,100 hectares for climate '2'. Similarly there is a small reduction in the area of oilseed rape with a change in climate. The estimated area of oilseed rape changes from 11,100 hectares for climate '0' to 10,000 hectares for climate '1' and to 10,700 hectares for climate '2'.

Table 9-4. Results of Base Runs.
Crop Areas (hectares, 000's)

Climate	'0'	'1'	'2'
Grass	92.1	199.9	194.5
Grass / Clover	1369.9	1159.9	1146.1
Spring Barley	42.2	41.4	18.8
Winter Barley	19.1	12.6	7.4
Winter Wheat	2.5	0.2	1.7
Potatoes	11.4	11.6	13.1
Vining Peas	11.9	11.0	11.1
Oilseed Rape	11.1	10.0	10.7

Table 9-5. Results of Base Runs.
Crop Yields[139] (tonnes. hectare^{-1})

Climate	'0'	'1'	'2'
Grass	4.9	5.3	5.5
Grass / Clover	3.7	3.8	3.8
Spring Barley	6.4	6.5	7.6
Winter Barley	10.7	8.3	8.1
Winter Wheat	5.6	5.9	5.9
Potatoes	17.7	21.7	20.8
Vining Peas	7.7	7.8	9.0
Oilseed Rape	4.6	3.7	3.3

The mean yields of the cash and forage crops are presented in Table 9-5. Data that relates to variations in regional yields can be found in Appendix 11-2. In general the regional estimates reflect the differences in potential yield that are reported in Appendix 6. Also, in the majority of cases inorganic nitrogen and pesticides are applied at the maximum rates permitted in the model.

With regard to grass and grass / clover there is a small increase in the per hectare production of leaf material with a change in climate. The average production from grass increases from 4.9 tonnes per hectare for climate '0' to 5.3 tonnes per hectare for climate '1' and to 5.5 tonnes per hectare for climate '2'. In the case of grass / clover the average yield for climate '0' is 3.7 tonnes / hectare. This increases to 3.8 tonnes per hectare for both climates '1' and '2'. It should be noted that when the changes in the areas of grass and grass / clover are considered in conjunction with productivity changes there is little difference between the climates in terms of total production of leaf material. However, there are differences between the climates in terms of the timing of forage production. In the case of the current climate peak production tends to occur later and autumn production tends to be higher than for climates '1' and '2'.

There is an increase in the average yield of spring barley, winter wheat, potatoes and vining peas with changes in climate, but for winter barley and oilseed rape the average yield declines with a change in climate. In the case of spring barley there is relatively little difference between climates '0' and '1' in terms of total production. However, for climate '2', although there is an increase in per hectare production of

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[139] The crop yields are defined in tonnes DM hectare^{-1}except for potatoes which are defined as tonnes wet material hectare^{-1}.

approximately 19 percent there is a large decline in the planted area which results in a drop in national production of 47 percent; that is from 270,000 tonnes to 143,000 tonnes. For winter barley there is a reduction in both the area and productivity of crops with a change in climate which results in a fall in national production from 204,000 tonnes for climate '0' to 105,000 tonnes for climate '1' and 56,000 tonnes for climate '2'.

With regard to winter wheat there is a small increase in crop productivity with a change in climate. However, because the area of wheat falls there is a reduction in total production with climatic change. The model estimates of wheat production are 14,000 tonnes for climate '0', 1,200 tonnes for climate '1' and 10,000 tonnes for climate '2'. In the case of potatoes there is an increase in both crop area and per hectare production which results in an increase in the national crop from 202,000 tonnes for climate '0' to 252,000 tonnes for climate '1' and 273,000 tonnes for climate '2'. For peas the increase in per hectare productivity that is associated with a change in climate tends to be offset by reductions in planted area so that the production of peas varies between 92,000 tonnes for climate '0', 86,000 tonnes for climate '1' and 100,000 tonnes for climate '2'.

The last of the crops to be considered is oilseed rape. As with winter wheat there is a reduction in both crop area and per hectare productivity with a change in climate. However, the extent of the reduction in national production is less for oilseed rape than for winter wheat. The model estimates of total oilseed rape production vary between 51,000 tonnes for climate '0', 37,000 tonnes for climate '1' and 35,000 tonnes for climate '2'. These represent declines of 27 and 31 percent between climates '0' and '1' and climates '0' and '2', respectively.

9.1.3 Labour.

A summary of labour requirements is included in Table 9-6. Information relating to regional variations in labour requirements are presented in Appendix 11-3. From these sources it can be seen that the pattern of changes in labour requirements that emerges with variations in climate differs between farm types. Overall there is a decline in the requirements for labour on farms that involve livestock operations, with the exception of 'cropping and cattle' farms, and an increase in labour requirements on 'cropping', and 'cropping and cattle' farms. On 'cattle and sheep' farms the requirements for fixed and overtime labour and also for casual labour declines with a change in climate. In the case of 'sheep' farms, the requirements for casual labour are slightly higher for climate '2' than for climate '0', however, the reduction in fixed and overtime labour means that there is a net fall in the requirement for labour with a change in climate. The decline in labour requirements is a consequence of the fall in sheep numbers with changes in climate (see Table 9-3).

Table 9-6. Results of Base Runs. Labour (man days, 000's)

	Farm	Climate '0'	Climate '1'	Climate '2'
Fixed & Overtime	'Cattle and sheep'	1216	1074	1071
	'Dairy'	557	586	586
	'Sheep'	476	455	452
	'Cropping'	1249	1479	1806
	'Cropping and cattle'	144	187	191
	Scotland	3642	3781	4106
Casual	'Cattle and sheep'	164	133	134
	'Dairy'	79	28	25
	'Sheep'	63	60	64
	'Cropping'	223	188	243
	'Cropping and cattle'	26	10	11
	Scotland	555	419	477

On 'dairy' farms there is an increased requirement for fixed and overtime labour and a decreased requirement for casual labour with a change in climate. The net effect of these changes is for the total labour requirement to decline with changes in climate. The reasons for these changes are not entirely clear but it is likely that they are related to the lower requirements for housing animals. This compares with 'cropping' farms, where the requirement for fixed and overtime labour increases with climatic change. In contrast, there is a decline in the demand for casual labour between climates '0' and '1', but between climates '0' and '2' there is an increase in the demand for casual labour. The net effect of these changes is for labour requirements to increase with a change in climate. A partial explanation for the variations in the demand for labour on 'cropping' farms is related to increases in labour intensive crops such as potatoes with changes in climate. However, it appears that the main reason for the increase in labour requirements is that there is an average increase in the per hectare requirements for labour by the various crops (for further discussion see Section 9.2.3).

The last farm type to be considered are 'cropping and cattle' farms which are the smallest farm group to be modelled. From Table 9-6 it can be seen that there is an increase in the requirement for fixed and overtime labour but a decrease in casual labour with a change in climate. The net effect of these changes is for labour demand to increase with climatic change. On farms that involve livestock there tends to be a reduction in labour requirements with climatic change. Conversely on farms that involve cropping, there is an increase in labour, as the climate changes. In the case of the 'cropping and cattle' farm type it appears that changes in labour demands that result from climatic change are dominated by the changes associated with cropping.

With respect to the individual labour classes a change in climate appears to involve an increase in the demand for fixed and overtime labour coupled with a reduction in demand for casual labour. On a national basis the demand for fixed labour increases from 3.64 m man days for climate '0' to 3.78 m man days for climate '1' and 4.11 m man days for climate '2'. This compares with climate '0' where the estimates for climate '1' and '2' correspond to changes of approximately +4 and +13 percent. In the case of casual labour the national estimates vary between 0.56 m, 0.42 m and 0.48 m man days for climates '0', '1' and '2', respectively. In percentage terms these represent changes of -24 percent between climates '0' and '1', and -14 percent between climates '0' and '2'. However, if the sum of the labour classes (that is fixed, overtime and casual labour) are considered there is little difference between climate '0' and '1' but between climates '0' and '2' there is an increase of approximately 9 percent from 4.20 m to 4.58 m man days.

9.1.4 Financial Results.

The outputs of the base runs that relate to monthly variations in the financial status of different farm types are presented in Figure 9-1. The coefficients that are included in Figure 9-1 refer to variations in the current account and overdraft during the year and therefore account for repayments of capital and interest on long term debts (see Section 7.3). For this reason the variations in cash position tend to be greater than the associated changes in income might suggest. However, by including long term debts in the estimates of the financial position a better indication of changes in the viability of farms should be achieved than if these effects were not considered.

In terms of aggregate changes in the financial status of Scottish farms there is a decline between climates '0' and '1' of approximately 20 percent and between climates '0' and '2' there is a decline of 26 percent. That is from £ 563.2 m for climate '0' to £ 446.7 m for climate '1' and £ 417.0 m for climate '2'. However, the extent of these changes is not uniform across either farm types or regions. In percentage terms the magnitude of the declines in financial status with changes in climate tend to be similar for 'cattle and sheep', 'dairy', and 'sheep' farms. However, there is an improvement in the financial position of 'cropping' farms with a change in climate, while 'cropping and cattle' farms are comparatively unaffected by climate.

From Figure 9-1 it can be seen that the decline in the financial position of 'cattle and sheep' farmers with a change in climate is greatest at Paisley where the difference between climate '0' and climates '1' and '2' is approximately 40 percent. In contrast 'cattle and sheep' farms at Mylnefield are relatively unaffected by a change in climate. The responses in the financial status of the other regions are intermediate to those at Paisley and Mylnefield. At the national level the end of year cash position of 'cattle and sheep' farms varies from £ 276.0 m for climate '0', to £ 210.2 m for climate '1' and £ 192.0 m for climate '2'. These represent changes from climate '0' of approximately -24 and -30 percent, respectively.

In the case of 'dairy' farms the percentage differences between climates are similar to those found for 'cattle and sheep' farms. Paisley is the most significant region in terms of milk production and is also most affected by a change in climate. In comparison, Kinloss and Mylnefield are relatively unaffected by climatic change. Wick is the smallest dairy region but in percentage terms the decline in financial position with a change in climate is similar to that found at Paisley. At the national level the end of year cash position varies from £ 145.5 m for climate '0' to £ 112.0 m for climate '1' and £ 100.8 m for climate '2'. These correspond to differences between climate '0' and climates '1' and '2' of -23 and -31 percent, respectively.

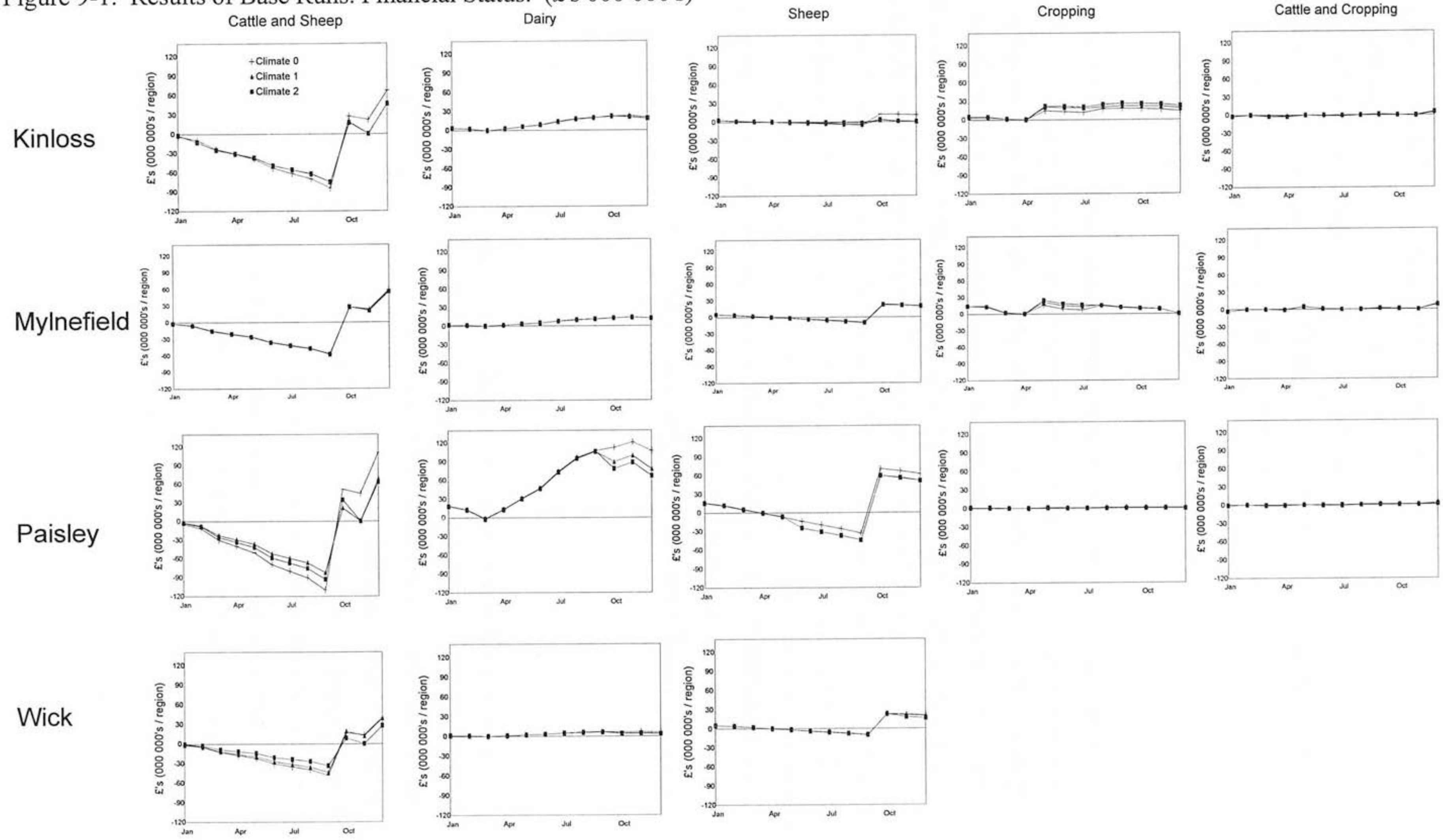
On 'sheep' farms there tends to be a decline in financial position with a change in climate. Between climate '0' and climates '1' and '2' there is a change in the current account of approximately -18 percent at Paisley. In contrast there is little difference between climates at Mylnefield. At Wick, there is an increase of approximately 1 percent in the end of year cash position between climates '0' and '1' but between climates '0' and '2' the current account falls by approximately 19 percent. At Kinloss the end of year financial position declines from £ 10.6 m for climate '0' to £ 0 for climates '1' and '2'. This result suggests that at Kinloss, 'sheep' farms are only marginally economic. At the national level the end of year financial position declines from £ 112.2 m for climate '0' to £ 90.8 m for climate '1' and £ 87.2 m for climate '2'. These represent changes from the current situation of -19 and -22 percent, respectively.

On 'cropping' farms there is an overall improvement in financial status with a change in climate. At Mylnefield and Paisley there is little variation between the climates but at Kinloss the end of year cash position increases from £ 13.6 m for climate '0' to £ 18.6 m for climate '1' and £ 22.0 m for climate '2'. The changes in the end of year cash positions of the various regions correspond to a national level increase between climate '0' and climates '1' and '2' of 38 and 56 percent, respectively. These changes are quite large and are dominated by the changes at Kinloss.

The last of the farm types to be considered are 'cropping and cattle' farms. At Paisley there is a large relative fall in the end of year financial position of approximately 50 percent with a change in climate. This tends to be balanced by improvements in the financial position of farms at Kinloss. At Mylnefield the financial status of 'cropping and cattle' farms are relatively unaffected by changes in climate. The net effect of the regional variations is for the end of year financial status to decline from £ 15.9 m for climate '0' to £ 15.0 m for climate '1' and £ 15.5 m for climate '2'. These correspond to national level changes relative to climate '0' of approximately -5 and -3 percent, respectively.

If the combined effects of changes in the financial status of the various farm types are considered, then Paisley is the area that is most affected by a change in climate while Mylnefield is least affected. At Paisley the end of year financial position declines from £ 282.4 m for climate '0' to £ 198.2 m for climate '1' and £ 181.6 m for climate '2'. These correspond to declines from climate '0' of 30 and 36 percent, respectively. At Mylnefield the end of year financial position varies from £ 99.2 m for climate '0' to £ 97.1 m for climate '1', and £ 95.3 m for climate '2'. At Kinloss the end of year financial position changes from £ 115.8 m for climate '0' to £ 88.5 m for

Figure 9-1. Results of Base Runs. Financial Status. (£'s 000 000's)



climate '1' and £ 92.7 m for climate '2'. These represent changes of -24 percent between climates '0' and '1' and -20 percent between climates '0' and '2'. At Wick there is a relatively small decline in the financial position of 4 percent between climates '0' and '1'. However, for climate '2' the end of year cash position is £ 47.4 m or a decline of 28 percent compared with climate '0'.

9.2 Sensitivity Analysis.

The purpose of this experiment is to investigate the robustness of farming systems that rely on cash crops versus those that involve the sale of livestock products. To achieve this the sensitivity of the model solution is evaluated with respect to changes in the potential yield of crops and pasture. Specifically, the potential growth of animal and machine harvested crops[140] are each altered by plus or minus 15 percent of the original estimates (see Section 5.3). To simplify matters and reduce the computational requirements of the experiment only the results from climates '0' and '1' are presented. The experiment, therefore, forms a two (cash crops) * two (forage crops) * two (climates) factorial. Otherwise the experiments performed in this section are the same as the base runs discussed in the preceding section. In particular the right hand side coefficients that determine the allocation of animals and land between the various farm types are the same as those included in Appendix 3.

9.2.1 Animal Numbers.

The outputs from the sensitivity experiments that relate to changes in animal numbers are presented in Table 9-7. From Table 5-9 it can be seen that there are no variations between any of the included treatments in the numbers of dairy cows and beef cattle. In this respect the outputs are similar to the base runs which showed that the numbers of dairy cows and beef cattle are relatively insensitive to changes in feed production. In contrast sheep numbers are sensitive to changes in climate. In general sheep numbers are higher for the current climate (climate '0') than for climate '1', but there are regional variations in the sensitivity of sheep numbers to changes in climate.

Kinloss is the region that is most affected both by changes in climate and by changes in the yield of forage crops. In the treatments that involve altering the yield

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[140] In the discussion animal harvested crops refer to grass, grass / clover and swedes while machine harvested crops refer to the other crops that are represented in the model.

of cash crops there is a decline in sheep numbers between climates '0' and '1', of approximately 30 percent. Further, there is a reduction in sheep numbers of approximately 38 percent between the climate '0' scenarios that involve an increase versus a decrease in forage production. The reduction in sheep numbers that result from a decline in forage production are greater, therefore, than the declines associated with climatic change. In contrast, at Mylnefield sheep numbers appear to be relatively unaffected by a change in climate or by changes in the relative productivity of cash and forage crops.

Table 9-7. Results of Sensitivity Analysis. Animal Numbers (000's)

Cash Crops =		-15 %		+15 %		+0 %		+0 %	
Forage Crops =		+0 %		+0 %		-15 %		+15 %	
Climate		'0'	'1'	'0'	'1'	'0'	'1'	'0'	'1'
Kinloss	Beef	126	126	126	126	126	126	126	126
	Dairy	33	33	33	33	33	33	33	33
	Sheep	980	653	980	656	608	540	980	739
Mylnefield	Beef	109	109	109	109	109	109	109	109
	Dairy	19	19	19	19	19	19	19	19
	Sheep	884	884	884	884	857	849	884	884
Paisley	Beef	166	166	166	166	166	166	166	166
	Dairy	180	180	180	180	180	180	180	180
	Sheep	1985	1660	1985	1629	1774	1592	1985	1573
Wick	Beef	66	66	66	66	66	66	66	66
	Dairy	12	12	12	12	12	12	12	12
	Sheep	736	663	736	663	682	622	725	730
Scotland	Beef	467	467	467	467	467	467	467	467
	Dairy	244	244	244	244	244	244	244	244
	Sheep	4585	3860	4585	3832	3921	3603	4574	3926

Although at Paisley and Wick the changes are less extreme than those observed at Kinloss there are similarities between the regions in terms of the patterns of variations in sheep numbers with changes in climate and with variations in the relative productivity of forage and cash crops. Two exceptions to this are that at Paisley there is a greater number of sheep in the treatment that involves climate '1' and a decrease in forage production than in the climate '1' treatment where there is an increase in forage production; and at Wick in the model runs that involve an increase in forage yield there is a slightly greater number of sheep for climate '1' than for climate '0'. However, it should be noted that the magnitude of these differences are small.

At the national level, there is little difference in the estimates of sheep numbers between the model runs that involve varying the relative yield of cash crops. For these same runs there is a difference of approximately -16 percent between climates '0' and '1'. Between the treatments that involve an increase versus a decrease in the productivity of forage crops there is a fall in sheep numbers of approximately 14 percent for climate '0'. The magnitude of this change is similar, therefore, to the effect of a change in climate in the experiments where the productivity of cash crops is varied. In the model runs where the productivity of forage is reduced there is a decline in sheep numbers of approximately 8 percent between climates '0' and '1'. A similar comparison for the experiments that involve an increase in forage yields shows a decline of 14 percent in sheep numbers between climates '0' and '1'. Further, there is little difference in sheep numbers between the experiment that involves an increase in forage production and the experiments that relate to changes in the yield of cash crops. The results suggest that sheep numbers are less sensitive to an increase than to a decrease in forage yields.

9.2.2 Area and Yield of Crops.

The results of the sensitivity analysis that relate to changes in crop areas are included in Table 9-8. Data that refer to regional changes in crop areas can be found in Appendix 11-4. As in the base experiments reported in Section 9.1 the crop areas appear to be more sensitive than livestock numbers to a change in climate. Also, for a given climate, the area of grass and grass / clover does not appear to be sensitive to a change in the productivity of cash crops. Further, there is little difference in the area of grass and grass / clover between the climate '1' scenarios for any of the experiments reported in Table 9-8. However, in the experiments that relate to climate '0' and which involve a change in the productivity of forage crops the areas of grass and grass / clover vary from the estimates achieved in the experiments that involve altering the yield of cash crops.

In the experiments where the yield of cash crops is altered, although the areas of grass and grass / clover are sensitive to a change in climate, they do not appear to be affected by increases versus decreases in the yield of the cash crops. In contrast climate appears to have less influence on the areas of grass and grass / clover in the experiments where the yield of forage crops is altered. In the experiments where the productivity of forage declines there is a change between climates ‘0’ and ‘1’ of -5 percent in grass and approximately -7 percent in grass / clover. In the experiments where the yield of forage crops are increased, between climates ‘0’ and ‘1’ there is an increase in the area of grass of 64 percent (or approximately half of the increase where the yield of cash crops is varied) and a decline in grass / clover of approximately 13 percent.

Table 9-8. Results of Sensitivity Analysis. Crop Areas (hectares, 000’s)

Cash Crops = Forage Crops =	-15 % +0 %		+15 % +0 %		+0 % -15 %		+0 % +15 %	
Climate	‘0’	‘1’	‘0’	‘1’	‘0’	‘1’	‘0’	‘1’
Grass	91.4	199.0	92.9	198.6	210.1	199.3	121.6	199.7
Grass / Clover	1370.1	1164.6	1369.9	1161.4	1252.1	1169.2	1339.3	1170.5
Spring Barley	40.8	41.7	44.9	41.1	42.3	44.3	42.3	41.4
Winter Barley	21.0	16.4	17.2	16.0	19.5	16.3	18.2	21.7
Winter Wheat	5.3	2.0	1.9	6.3	3.9	1.5	2.8	1.1
Potatoes	12.1	13.0	10.9	10.9	11.8	11.9	11.7	11.0
Vining Peas	12.3	11.9	11.3	11.1	12.5	11.4	12.0	12.1
Oilseed Rape	10.6	10.8	11.0	10.5	12.1	11.1	12.2	11.6

In comparison cereal crops are sensitive both to changes in climate and to the changes imposed on the relative yields of cash and forage crops. Further, the variations in the areas of the cereal crops that are due to climatic change tend to be similar in magnitude (but not necessarily in sign), to the differences that arise with changes in the relative yields of cash and forage crops. Spring barley is the least sensitive of the cereal crops to a change in climate and it is followed in increasing order of sensitivity by winter barley and winter wheat. In the experiments that involve reducing the yield of cash and forage crops there are small increases of between 2 and 5 percent in the area of spring barley with a change in climate. This is in contrast to the experiments where the productivity of cash and forage crops are increased as there are declines in the area of spring barley with a change in climate of 2 and 8 percent.

With regard to winter barley there is a decline in area with a change in climate of 7 and 22 percent in the experiments where the yield of cash crops is altered and 16 percent in the experiment where the yield of forage crops are reduced. In the experiment where the yield of forage crops is increased there is an increase in the area of winter barley of 19 percent. Further, there is a decline in the area of winter wheat with a change in climate of approximately 60 percent in the experiments where the yield of forage crops is altered and in the experiment where there is a reduction in the yield of cash crops. These compare with an increase of approximately 230 percent in the experiment that involves an increase in the yield of forage crops.

The remaining crops to be considered are potatoes, vining peas and oilseed rape. As in the base runs these crops tend to be less sensitive to a change in climate than the cereal crops. Also, the areas of these crops tend to be relatively stable in terms of changes in the relative yield of cash and forage crops. In the case of potatoes there is a small increase of 7 percent between climates '0' and '1' in the experiment that involves a reduction in the yield of cash crops. In the experiment where the productivity of cash crops are increased and in the experiment that involves a reduction in the yield of forage crops, there is little difference in the area of potatoes between climatic scenarios. This compares with a reduction of 6 percent between climate scenarios in the experiment that involves an increase in the yield of forage crops.

In the experiments where the yield of cash crops are altered and in the experiment where the yield of forage crops is decreased there are declines in the area of vining peas with a change in climate; the extent of these declines ranges from 2 to 9 percent. This compares with a small increase of approximately 1 percent in the area of vining peas, with a change in climate, in the experiment where there is an increase in the productivity of forage crops. In the case of oilseed rape there is an increase in area of approximately 2 percent with a change in climate in the experiment where the yield of cash crops declines. In the other experiments there are reductions of approximately 5 to 8 percent in the area of oilseed rape with changes in climate.

The results of the sensitivity analysis that refer to crop yields are presented in Table 9-9 and Appendix 11-5. From Table 9-9 it can be seen that differences in crop yields that arise with a change in climate are similar to the changes that are observed in the base runs. Further, the magnitude of the variations in yield closely reflect the scale of the changes imposed on potential production. In the experiments that involve changing the yield of cash crops there is little difference in total forage production (that is the product of area and yield) between any of the treatments. Also, in experiments where the potential yield of forage crops is altered, there is little difference between climates in terms of total forage production. However, between the experiments where the yield of forage crops is altered, the differences in forage production are similar to the changes imposed on the productivity of forage crops, that is plus or minus 15 percent of the predictions associated with the base runs.

Table 9-9. Results of Sensitivity Analysis. Crop Yields[141] (tonnes. hectare^{-1})

Cash Crops =	-15 %		+15 %		+0 %		+0 %	
Forage Crops =	+0 %		+0 %		-15 %		+15 %	
Climate	'0'	'1'	'0'	'1'	'0'	'1'	'0'	'1'
Grass	4.9	5.3	4.9	5.3	4.2	4.5	5.7	6.1
Grass / Clover	3.7	3.8	3.7	3.8	3.1	3.2	4.2	4.4
Spring Barley	5.7	5.8	6.9	7.1	6.4	6.6	6.4	6.5
Winter Barley	9.7	7.5	12.4	9.4	10.9	8.4	10.5	8.3
Winter Wheat	5.2	5.6	5.8	8.5	5.6	6.2	6.0	6.2
Potatoes	15.2	18.5	20.3	24.9	17.8	21.7	17.8	21.7
Vining Peas	6.7	6.7	8.7	8.8	7.7	7.8	7.7	7.8
Oilseed Rape	4.1	3.2	5.1	4.1	4.7	3.6	4.7	3.7

Spring barley is the least sensitive of the cereals to a change in climate and in increasing order of sensitivity it is followed by winter barley and winter wheat. However, it should be noted that relative changes in the aggregate production of cereal crops that occur with changes in climate tend to be smaller than changes in individual crops. As a result, the magnitude of climate related changes in cereal production range from -5 to -19 percent. These compare with climate related changes in winter wheat production of -59 and +386 percent in the experiments that involve a decrease and an increase in the potential yield of cash crops, respectively.

A further point is that the ranking of the experimental treatments in terms of total cereal production varies depending on the climate that is considered. In descending order of productivity the climate '0' experiments are ranked as (1) +15 percent in the potential yield of cash crops, (2) -15 percent in the potential yield of forage crops, (3) +15 percent in the potential yield of forage crops and (4) -15 percent in the yield of cash crops. These correspond to production levels of 464,000 and 534,000 tonnes for the least and most productive experimental treatments or a difference of +15 percent. In the climate '1' scenarios the order of the experiments that involve altering the productivity of forage crops is the reverse of the climate '0' scenarios and total cereal production varies from 376,000 and 496,000 tonnes or a difference of +32 percent.

With regard to potatoes, there are increases in production of between 15 and 31 percent with a change in climate. In comparison, potatoes are less influenced by the changes imposed on the relative yields of cash and forage crops. In the case of vining

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[141] The crop yields are defined in tonnes DM hectare^{-1}except for potatoes which are defined as tonnes wet material hectare^{-1}.

peas, only small differences in production can be attributed to climate change, however, the relative effect of changes in potential crop production tend to be greater than for potatoes. These compare with reductions in the production of oilseed rape of between 20 and 30 percent with a change in climate, and an increase in production of between 14 and 32 percent between the experiment that involves a decrease in the yield of cash crops and the other experiments where the potential productivity of crops are altered.

9.2.3 Labour.

The labour requirements that are associated with the sensitivity analysis are reported for each farm type in Table 9-10. A regional breakdown of these estimates is presented in Appendix 11-6. In general there is an increased reliance on fixed and overtime labour and a decreased requirement for casual and part time labour with a change in climate. This is because climatic change reduces the seasonality of labour requirements and therefore allows relatively expensive casual labour to be substituted for by fixed and overtime labour. At the national level the requirement for fixed and overtime labour increases with a change in climate by between 12 percent in the experiment where the yield of cash crops is reduced and 2 percent in the experiment where the yield of cash crops is increased. In the same experiments there is a reduction in the national requirements for casual labour of 18 and 15 percent, respectively. The net effect of these changes is for the total labour requirements to increase by between 0 and 8 percent with a change in climate.

With respect to the individual farm types there is a reduction in both fixed and overtime labour and casual labour on 'cattle and sheep' farms with a change in climate. The magnitude of these reductions tend to be greater for casual labour, ranging from 6 to 16 percent, than for fixed labour where the reductions are between 3 and 9 percent. These correspond to reductions in the overall requirement for labour of between 3 and 10 percent. In the case of 'dairy' farms there is an increase in fixed and overtime labour of approximately 5 percent while reductions in casual labour are in the order of 60 percent. The net effect of these changes is for the total labour requirements on 'dairy' farms to decline by approximately 3 percent with a change in climate.

On 'sheep' farms there is a reduced requirement for labour with a change in climate. The extent of these reductions range between 1 and 5 percent for fixed and overtime labour and between 0 and 6 percent for casual labour. The overall effect of these changes is for labour requirements to decline by between 1 and 4 percent with a change in climate. On 'cropping' farms the relative changes in labour requirements with changes in climate range between +9 and +39 percent for fixed and overtime labour and between -3 and +20 percent for casual labour. These correspond to increases in overall labour requirements of between 8 and 33 percent. In the case of 'cropping and cattle' farms the requirements for fixed and overtime labour increase by 17 to 39 percent and casual labour decrease by 36 to 62 percent with a change in climate. On this farm type the net effect of climate change is for labour requirements to increase by between 11 and 15 percent.

Table 9-10. Results of Sensitivity Analysis. Labour (man days, 000's)

Cash Crops = Forage Crops =		-15 % +0 %		+15 % +0 %		+0 % -15 %		+0 % +15 %	
Climate		'0'	'1'	'0'	'1'	'0'	'1'	'0'	'1'
Fixed & Overtime	'Cattle and sheep'	1216	1112	1216	1104	1106	1071	1216	1102
	'Dairy'	557	585	557	585	559	585	559	586
	'Sheep'	476	454	476	455	458	452	476	460
	'Cropping'	1249	1736	1562	1702	1423	1632	1423	1806
	'Cropping and cattle'	144	185	163	191	148	185	147	177
	Scotland	3642	4072	3974	4037	3694	3925	3821	4131
Casual	'Cattle and sheep'	164	142	164	140	141	133	164	138
	'Dairy'	78	29	79	29	78	31	73	25
	'Sheep'	64	62	64	62	62	62	64	60
	'Cropping'	193	188	213	218	203	208	203	243
	'Cropping and cattle'	26	10	22	14	25	13	24	12
	Scotland	525	431	542	463	509	447	528	478

On the farms that involve livestock operations (with the exception of 'cropping and cattle' farms) there is a tendency for the overall requirements for labour to decline with a change in climate. In part this is due to reductions in the requirements for animal housing and in this respect the results of the sensitivity analysis are similar to the base runs. Another reason for the decline in labour requirements with a change in climate, at least on farms where sheep are present, is related to the decline in sheep numbers.

These compare with 'cropping', and 'cropping and cattle' farms where there is an increase in total labour requirements with a change in climate. However, variations in the areas and yields of crops that occur with climate change do not fully explain this result. As in the base runs the principle reason for the increase in labour requirements is related to the increased availability of working hours with a change in climate. That is farmers have more time to perform cultivation and harvesting operations and they utilise this time by using smaller items of machinery and by being less reliant on contracting services (see Section 7.1). In the results there is evidence that this occurs as there is an average increase in the per hectare labour requirements of the various crops.

The experimental treatments that involve varying the productivity of cash and forage crops tend to have less effect, than the climate change scenarios, on labour demand. At the national level an increase in the potential yield of cash crops from -15 to +15 percent of the original estimates results in a net increase of 8 percent and no change in labour requirements for climates '0' and '1', respectively. With respect to the individual farm types, the farms that involve livestock (with the exception of 'cropping and cattle' farms), are relatively unaffected by changes in the potential production of cash crops. However, on 'cropping', and 'cropping and cattle' farms there are increases in labour requirements with increases in the potential yield of cash crops of between 9 and 23 percent for climate '0', and between 0 and 5 percent for climate '1'. This result is related to an association between increases in the yield of cash crops and the amount of labour that is needed to harvest and store the resulting produce.

In the experiments that involve altering the yield of forage crops there are increases in national labour requirements with increases in yield of 3 and 5 percent for climates '0' and '1', respectively. On 'cropping' farms and on farms where sheep are present there are increases in labour requirements with increases in forage yield of between 0 and 11 percent for climate '0' and from 3 to 11 percent for climate '1'. On 'dairy' farms and 'cropping and cattle' farms there are reductions in total labour requirements with increases in forage yield of approximately 1 percent for climate '0' and 1 to 5 percent for climate '1'.

On 'cattle and sheep', and 'sheep' farms the increase in the requirements for labour with increases in forage production are primarily related to changes in sheep numbers. This compares with the 'dairy', and the 'cropping and cattle' farms where an increase in forage yields tends to reduce the requirement for forage conservation and hence requirements for labour. However, the reason that increases in forage yields lead to increases in labour requirements on ‘cropping’ farms is less clear. The main reason for this is that an increase in forage production allows ‘cropping’ farms to reduce the area of cereal crops that are grown for animal feed; and in turn this releases resources for more labour intensive crops to be planted.

9.2.4 Financial Results.

The financial results of the sensitivity analyses are in Table 9-11 and a regional breakdown of these outcomes is included in Appendix 11-7. At the national level there are declines in the closing cash position of farms with a change in climate of between 8 percent and 19 percent. In the treatments that involve altering the potential production of crops there is relatively little difference between cash or forage crops in terms of their influence on the aggregate financial position of Scottish farms. Thus, for a given climate, an increase in the potential yield of forage crops has a comparable effect to an increase in the yield of cash crops. Similarly, with the exception of the climate ‘0’ scenario, the outcomes associated with decreases in the yield of forage crops are similar to those involving decreases in the yield of cash crops.

Table 9-11. Results of Sensitivity Analysis.
End of Year Cash Position (£, 000,000’s).

Cash Crops =	-15 %		+15 %		+0 %		+0 %	
Forage Crops =	+0 %		+0 %		-15 %		+15 %	
Climate	‘0’	‘1’	‘0’	‘1’	‘0’	‘1’	‘0’	‘1’
‘Cattle and sheep’	276.0	215.3	276.0	215.7	214.8	200.9	280.2	211.2
‘Dairy’	141.8	112.5	150.1	118.8	137.5	121.6	145.7	119.9
‘Sheep’	112.0	90.8	112.2	90.8	104.7	89.1	114.8	96.8
‘Cropping’	10.0	16.7	17.8	25.7	14.3	21.2	13.9	21.1
‘Cropping and cattle’	13.6	13.5	16.5	21.7	15.1	15.2	15.7	14.4
Scotland	553.4	448.8	572.6	472.7	486.4	448.0	570.3	463.4

With the exception of ‘cropping’ and ‘cropping and cattle’ farms, there tends to be a decline in the financial status of farms with a change in climate. On farms where cropping occurs, changes in financial status that are the result of changes in climate range between -8 and +67 percent. Of the other farm types, ‘cattle and sheep’ farms are the most sensitive to a change in climate. On this farm type there are declines in financial position with changes in climate that range between 6 percent for the scenario involving a decrease in forage productivity and 25 percent for the scenario where there is an increase in forage productivity. In the scenarios that involve altering the yield of cash crops there is a decline of approximately 22 percent in financial status with a change in climate.

Further, for climate '0', there is a difference of approximately +30 percent in the financial status of 'cattle and sheep' farms between the scenarios that involve a decrease versus an increase in the potential yield of forage crops. A similar comparison for the climate '1' scenarios shows a 5 percent increase in final cash with increases in forage yield. In contrast, there is little difference in terms of sensitivity to climate between the treatments where the potential yield of cash crops is altered. In general the changes in financial status of 'cattle and sheep' farms reflect the changes in sheep production that occur with the differing climate and potential yield scenarios.

The pattern of changes in the financial status of 'dairy' farms with changes in the relative yield of crops is slightly different to 'cattle and sheep' farms. On 'dairy' farms there is an improvement of 6 percent in the financial position for the climate '0' scenarios that involve an increase in forage yields. This compares with the climate '1' scenario where there is a decline of approximately 2 percent between the treatment that involves reducing the yield of forage crops and the treatment where the yield of forage crops increases. Also, there are small variations in the financial status of 'dairy' farms with changes in the yield of cash crops. The principle reason for these changes is related to the cost of feeding animals as there is little difference between the scenarios in terms of milk production.

As on 'dairy' farms the financial status of 'sheep' farms are more sensitive to changes in climate than to changes in the relative yield of crops. On 'sheep' farms there is an increase in the final cash position of approximately 10 percent between the scenarios that involve a reduction in forage yield and the scenarios where forage yield increases. In contrast there is little difference between the treatments that involve altering the yield of cash crops. The magnitude of changes in the financial position of 'sheep' farms are similar therefore to those occurring on 'cattle and sheep' farms and can largely be explained by changes in sheep numbers.

Of the various farm types, 'cropping' farms are the most sensitive to a change in climate. On 'cropping' farms there are large improvements in financial position with changes in climate that range between +44 percent for the scenario where the relative yield of cash crops increases and +67 percent for the scenario where the yield of cash crops are reduced. In the scenarios where the yield of forage crops is altered, the variations in financial position that result from changes in climate, are intermediate to those involving changes in the yield of cash crops. In line with expectations 'cropping' farms are the most sensitive of the farm types to a change in the relative yield of cash crops. A comparison of the climate '0' scenarios shows an increase of 78 percent between the treatments that involve a decrease versus an increase in the potential yield of cash crops. A similar comparison of the climate '1' scenarios reveals a 54 percent increase in financial position. In contrast there is little variation between the treatments that involve altering the yield of forage crops. One of the reasons that the response to changes in climate and to alterations in the relative yield of cash crops are so large is that 'cropping' farms are the most indebted of the farm types. This means that a significant proportion of income is devoted to the repayment of fixed debts so that changes in income have a disproportional influence on the final cash position.

With regard to 'cropping and cattle' farms the most profitable scenario involves climate '1' and an increase in the relative yield of cash crops while the least profitable scenario involves climate '1' and a decrease in the yield of cash crops. On this farm type the financial outcomes that are associated with altering the relative yields of forage crops tend to be intermediate to the experiments that involve changing the yield of cash crops. In the experiments where the relative yield of cash crops is reduced there is a decline in financial status of 1 percent between climates '0' and '1'. This compares with an increase of 30 percent with a change in climate in the experiments where the yield of cash crops are increased. In the experiments where the yield of forage crops are altered the financial position varies with changes in climate by between +1 to -8 percent. Although the pattern of changes in the financial status of 'cropping and cattle' farms is relatively mixed, it reflects the relative changes in the profitability of livestock and cropping that occur on the previously discussed farm types.

9.3 Long Term Adjustments to Farming Systems.

The experiments that are included in this section are designed to evaluate long term adjustments in farming systems. To achieve this the sale and purchase of land is considered and there is provision to vary the maximum numbers of livestock that can be carried on the different farm types. The treatments that are included are two climatic scenarios (climates '0' and '1') and three stocking rates where the stocking rates represent changes of -15, 0 and +15 percent from the levels that are included in the preceding experiments. With regard to the sale and purchase of land the model is formulated to allow individual farm types to sell up to 15 percent of their land to other farm types that are in the same region.

An assumption of this experiment is that the changes in stocking rates and transfers of land from one farm type to another occur without cost. Also, the right hand side coefficients that refer to the initial cash position and repayments of fixed debts and casual labour are included at the same levels as the experiments reported in Sections 9.1 and 9.2. Although these assumptions involve a significant degree of simplification in terms of changes in the long term status of the farm types the results of the experiment should indicate the direction of changes in the structure of Scottish agriculture and also the influence that climate change has on these adjustments. The model outputs that are presented include the changes in the areas and productivity of crops, livestock numbers, labour requirements and the financial situation of the farm types and regions. In addition, the amount of land that is exchanged between the different farm types is discussed.

9.3.1 Sale and Purchase of Land.

The experimental results that relate to the amounts of land that are purchased and sold by the various farm types are presented in Table 9-12 and Appendix 11-8. From these sources it can be seen that land tends to be transferred from 'cattle and sheep', 'dairy', and 'sheep' farms to 'cropping and cattle', and 'cropping' farms but the size of the land transfers varies between regions, climates and stocking rates. In general, the amount of land that is exchanged is greater for climate '1' than for climate '0'. Also, in the case of climate '0' the amount of land that is transferred is lower for the high and low stocking rates than for the existing stocking rate. In contrast, land transfers are highest for the lowest and highest stocking rates, in the climate '1' scenarios. The largest land transfers occur for the climate '1' scenario and the lowest stocking rate. However, there are exceptions to these trends; most notably at Wick where there are no land sales or purchases and at Mylnefield, where with the exception of the current climate and existing stocking rate, transfers of land are small.

Table 9-12. Results of Land Selling and Purchasing Experiments.
Sale and Purchase of Land (hectares, 000's)

Animal Number =		-15 %		+0 %		+15 %	
Climate		'0'	'1'	'0'	'1'	'0'	'1'
Land Purchased	'Cattle and sheep'	0	0	0	0	0	0
	'Dairy'	0	0	0	0	0	0
	'Sheep'	0	0	0	0	0	0
	'Cropping'	6.2	0.7	3.9	5.0	6.0	6.9
	'Cropping and cattle'	0	10.7	4.4	1.5	0.2	0
Land Sold	'Cattle and sheep'	3.5	4.3	4.3	4.5	3.4	3.4
	'Dairy'	0.7	4.5	0.4	1.4	0.7	1.0
	'Sheep'	0.3	2.4	3.7	0.4	0.3	1.3
	'Cropping'	0	0	0	0	0.2	0
	'Cropping and cattle'	1.8	0.3	0	0.3	1.8	1.2

In the climate '1' scenarios the factors that influence the levels of land transfers at differing stocking rates are as follows: the high land transfers that take place at the lowest stocking rate occur as livestock farms are unable to utilise all of the forage that is produced; conversely, at the highest stocking rate because of the poor match between the seasonal supply and demand for forage (see Section 9.1.1) the requirements for feed grains become important. A related point is that because the production of feed grains is marginally economic they are only produced on 'cropping' farms in sufficient quantities to support livestock production. At low stocking rates, therefore, the variations in land transfers are driven by a surplus of land on livestock farms, while at high stocking rates they are dominated by the need for feed grains that are produced on 'cropping' farms.

With respect to the climate '0' scenarios the seasonal supply and demand for forage is better matched than in the climate '1' scenarios. The utilisation of pasture by animals is, therefore, higher for climate '0' than for the climate '1' scenarios. As a further point, given the current climate, the opportunities for 'cropping' farms to profitably use additional land are limited; this is because crop yields tend to be lower and there are fewer workable hours than in the climate '1' scenarios. For these reasons the level of land transfers tend to be lower for climate '0' than for climate '1'. As previously mentioned, the transfers of land from livestock to 'cropping' farms are smaller for the lowest and highest stocking rates than for the intermediate stocking rate. However, the magnitude of these differences are small and are related to variations in the transfer of land from 'sheep' farms.

At Paisley the amount of land that is exchanged tends to be greater than at Wick or Mylnefield particularly in the experiments that involve climate '1' and the current or reduced stocking rate. In the scenario that involves the current climate and the reduced stocking rate there is a transfer of land from 'cropping and cattle' farms to 'cropping' farms. However in the experiment with the current climate and existing stocking rate there is an exchange of land between 'sheep' farms and 'cropping and cattle' farms. In the experiment that involves the current climate and high stocking rate there is an exchange of land from 'cropping' farms to 'cropping and cattle' farms (the reverse of what occurred at the reduced stocking rate).

The pattern of land transfers that emerges at Paisley for climate '1' is somewhat different to the climate '0' scenarios. In the experiments where stocking rates are reduced there is a transfer of land from the farms that involve livestock (with the exception of 'cropping and cattle' farms) to farms where cropping occurs. In the experiments that involve the current stocking rate there is a transfer of land from 'dairy' farms to 'cropping' and to 'cropping and cattle' farms and in the experiment where the stocking rate is increased there are no sales or purchases of land.

Of the various regions Kinloss undergoes the most significant levels of structural adjustment with changes in climate and animal numbers. With the exception of the experiment involving climate '0' and the current stocking rate there is a transfer of land from 'cattle and sheep', 'dairy', and 'sheep' farms to 'cropping and cattle', and 'cropping' farms. In the case of the climate '0' and current stocking rate treatments there is a transfer of land from 'sheep' farms to 'cropping' farms. Further, the largest transfers occur with the reduced and increased stocking rates and with a change in climate. The size of the land transfers at Kinloss tend to be larger than the other regions and therefore have a major influence on the changes that are evident at the national level.

9.3.2 Animal Numbers.

The model predictions that relate to animal numbers can be found in Table 9-13. It can be seen that, with the exception of sheep, there is relatively little change between the climatic scenarios in terms of animal numbers. However, in the case of sheep numbers there are reductions of between 6 and 21 percent with changes in climate.

The areas that contribute to this decline are Kinloss, Paisley and Wick, while numbers at Mylnefield are relatively unaffected by climate.

Table 9-13. Results of Land Selling and Purchasing Experiments. Animal Numbers (000’s).

Animal Number =		-15 %		+0 %		+15 %	
Climate		‘0’	‘1’	‘0’	‘1’	‘0’	‘1’
Kinloss	Beef	107	107	126	126	126	128
	Dairy	28	28	33	33	38	38
	Sheep	833	736	980	643	1047	675
Mylnefield	Beef	93	93	109	109	113	109
	Dairy	16	16	19	19	21	21
	Sheep	751	751	884	884	979	997
Paisley	Beef	141	141	166	166	166	166
	Dairy	153	153	180	180	207	207
	Sheep	1687	1541	1985	1513	1956	1627
Wick	Beef	56	56	66	66	66	66
	Dairy	10	10	12	12	13	13
	Sheep	625	625	736	569	779	515
Scotland	Beef	397	397	467	467	471	469
	Dairy	207	207	244	244	279	268
	Sheep	3896	3653	4585	3609	4761	3814

In the treatments where the maximum stocking rate is altered there is an increase in total beef numbers between the low and intermediate stocking rate of 18 percent but there is little further change between the intermediate and high stocking rates. For both the low and intermediate stocking rates the numbers of beef animals equal the maximum livestock numbers that are permitted in the model solution. However, at the high stocking rate, it is feasible to carry larger numbers of animals but it appears that it is not economic for farmers to do so. In the case of dairy animals, in all of the experiments, the numbers are close to the maximum numbers permitted in the solution. In contrast sheep numbers are close to their respective upper limits in the experiments that involve the current climate and the low and intermediate stocking rates, but in all other runs, sheep numbers are less than the maximum allowed.

9.3.3 Area and Yield of Crops.

The model results that relate to crop areas and yields can be found in Table 9-14 and Table 9-15 and Appendices 12-9 and 12-10. The influence of climate on crop yields is similar to the estimates from the base runs. A further point is that crop yields do not appear to be sensitive to variations in stocking rates. For this reason the average yields for Scotland only differ from the base runs by a small amount due to inter-regional differences in the areas and yields of crops and because of changes in the soils that crops are planted on.

**Table 9-14. Results of Land Selling and Purchasing Experiments.
Crop Areas (hectares, 000's).**

Animal Number =	-15 %		+0 %		+15 %	
Climate	'0'	'1'	'0'	'1'	'0'	'1'
Grass	161.3	201.9	91.9	204.1	88.2	198.3
Grass / Clover	1251.1	1078.6	1364.7	1161.2	1369.9	1103.8
Spring Barley	28.2	21.8	33.7	21.6	28.9	32.4
Winter Barley	15.7	4.2	8.7	9.8	12.0	5.0
Winter Wheat	13.5	3.6	11.1	0.1	8.7	1.7
Potatoes	12.5	11.9	10.8	8.5	16.3	13.8
Vining Peas	13.2	9.2	16.3	11.8	9.9	5.2
Oilseed Rape	8.7	7.8	18.6	9.2	11.4	15.0

**Table 9-15. Results of Land Selling and Purchasing Experiments.
Crop Yields[142] (tonnes. hectare^{-1})**

Animal Number =	-15 %		+0 %		+15 %	
Climate	'0'	'1'	'0'	'1'	'0'	'1'
Grass	4.9	5.3	4.9	5.3	4.9	5.3
Grass / Clover	3.7	3.8	3.7	3.8	3.7	3.8
Spring Barley	6.3	6.7	6.3	6.8	6.3	6.6
Winter Barley	10.4	8.3	9.8	8.6	9.7	8.5
Winter Wheat	5.6	4.6	5.7	4.4	5.5	5.1
Potatoes	17.5	21.8	18.2	22.0	17.8	21.7
Vining Peas	7.6	7.7	7.9	7.7	7.5	7.7
Oilseed Rape	4.6	3.6	4.8	3.7	4.7	3.7

From Table 9-14 it can be seen for the climate '0' scenarios that there is a decrease in the area of grass with an increase in stocking rates. This corresponds to a decline in grass from the lowest to the highest stocking rate of 45 percent. In contrast there

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[142] The crop yields are defined in tonnes DM hectare^{-1} except for potatoes which are defined as tonnes wet material hectare^{-1}.

is little difference between the different stocking rates for the climate '1' scenarios in the area of grass. However, the effect of a change in climate is for the area of grass to increase between climates '0' and '1' by between 25 percent for the treatment that involves the reduced stocking rate and 125 percent where stocking rates are increased.

This compares with grass / clover swards where there tends to be a decline in the area planted with changes in climate. The extent of this decline ranges between 14 percent for the lowest stocking rate and 19 percent for the highest stocking rate. The effect of increasing the stocking rate from the lowest to the highest rate is to increase the area of grass / clover by 10 percent for the climate '0' scenario and by 2 percent for the climate '1' scenario. The relative changes in the areas of grass and grass / clover tend to compensate for each other so that differences in total forage production are less marked than those between individual crops. For all of the stocking rates, therefore, the inter-climate differences in total forage production are less than 5 percent.

The net effect of altering the stocking rate is for a small increase in forage production between the lowest and intermediate stocking rate. However, between the intermediate and highest stocking rate there is little difference between the climate '0' scenarios but there is a decline of approximately 5 percent for the climate '1' scenarios. In general the pattern of changes in forage production tend to reflect the changes in animal numbers that are discussed in Section 9.3.2. The largest amount of forage and the greatest number of animals occur in the scenario that involves climate '0' and the highest stocking rate while the smallest amount of forage and lowest animal numbers are associated with the treatment involving climate '1' and the lowest stocking rate.

In contrast to forage crops, cereals are considerably influenced by climatic change. There are increases in the area of spring barley, with a change in climate, at the high stocking rate and also in the area of winter barley at the existing stocking rate. These compare with reductions in area, between climates '0' and '1' of 22 to 99 percent for other cereal crops and stocking rates. Of the various cereals, winter wheat is the most affected by a change in climate and spring barley is the least affected. An increase in the stocking rate appears to result in a reduction in the total area of cereals in the climate '0' scenarios and an increase in the climate '1' scenarios. The total area of cereals is greatest, therefore, for climate '0' and the low stocking rate and least for climate '1' and the low stocking rate. Because of the pattern of these changes, the effect of an increase in stocking rate, is to reduce the impact of climate change on the area of cereals.

Of the remaining crops, with the exception of oilseed rape where there is an increase in area between climates '0' and '1' for the highest stocking rate, there tend to be decreases in the area of crops with a change in climate. In the case of potatoes, decreases in area with changes in climate range between 5 and 21 percent for the low and intermediate stocking rates, respectively. For vining peas the reductions in area with changes in climate range between 28 and 48 percent for the intermediate and high stocking rates, while for oilseed rape, the reductions in area with changes in climate range between 10 and 50 percent for the low and intermediate stocking rates.

With regard to the effect that stocking rate has on potatoes there is a decrease in area between the low and intermediate stocking rates of between 14 and 29 percent for climates '0' and '1', respectively. However, between the low and high stocking rates there is an increase in the area of potatoes of 30 percent for climate '0' and 16 percent for climate '1'. This contrasts with vining peas where there is an increase in area between the low and intermediate stocking rates but a reduction between the low and high stocking rates. In the case of oilseed rape there is an increase in area between the low and intermediate stocking rates and also between the low and high stocking rates. The overall effect, therefore, is for the total area of potatoes, peas and oilseed rape to increase with stocking rate.

Because of the differences between crops in terms of the influence of stocking rate the magnitude of changes in total area tend to be smaller than for individual crops. Between the low and intermediate stocking rates there is a difference in the total area of potatoes, peas and oilseed rape of +33 percent for climate '0' and +2 percent for climate '1'. This compares with the low and high stocking rates where the differences in area are +9 and +18 percent, for the climate '0' and climate '1' scenarios, respectively.

9.3.4 Labour.

The amount of labour that is used in each of the model runs is included in Table 9-16 and Appendix 11-11. From these sources it can be seen that the total labour requirements tend to be highest for the intermediate stocking rate and that variations in labour requirements tend to be greater for the climate ‘0’ scenarios than for climate ‘1’. For the current climate and the low stocking rate the estimate of the total labour requirement for Scotland is 4.04 m man days. This compares with 4.71 m man days or an increase of 17 percent for the scenario involving the current climate and the intermediate stocking rate. For the highest stocking rate and climate ‘0’ the total amount of labour that is required is 4.67 m man days or an increase of 16 percent over the treatments that involve the current climate and lowest stocking rate.

Table 9-16. Results of Land Selling and Purchasing Experiments. Labour (man days, 000’s)

Animal number =		-15 %		+0 %		+15 %	
Climate		‘0’	‘1’	‘0’	‘1’	‘0’	‘1’
Fixed & Overtime	‘Cattle and sheep’	1071	1072	1191	1079	1216	1075
	‘Dairy’	557	562	569	576	583	586
	‘Sheep’	457	452	474	466	476	474
	‘Cropping’	1260	1498	1806	1557	1668	1249
	‘Cropping and cattle’	144	183	169	175	191	190
	Scotland	3489	3767	4209	3853	4134	3574
Casual	‘Cattle and sheep’	144	133	159	135	164	134
	‘Dairy’	73	45	68	25	79	46
	‘Sheep’	62	60	62	62	63	64
	‘Cropping’	243	190	188	202	217	243
	‘Cropping and cattle’	26	13	26	12	13	10
	Scotland	548	441	503	436	536	497

In the case of the climate ‘1’ scenarios the total labour requirement for Scotland is 4.21 m man days for the lowest stocking rate and 4.29 m man days or an increase of 2 percent for the intermediate stocking rate. The labour requirement for the high stocking rate and climate ‘1’ is 4.07 m man days which represents a 3 percent decline compared with the lowest stocking rate. A comparison of differences between climates shows a small increase in total labour requirements of 4 percent for the lowest stocking rate. In contrast there are declines in total labour requirements for the intermediate and high stocking rate of 9 and 13 percent with a change in climate.

In the climate ‘0’ scenarios there is an increase in the total demand for labour between the lowest and intermediate stocking rates of 15 percent and between the lowest and highest stocking rates of 20 percent. For the climate ‘1’ scenarios there is a small reduction of 5 percent between the lowest and intermediate stocking rates and an increase of 2 percent between the lowest and highest stocking rates. The effect of an increase in stocking rate is, therefore, dependent on the climate that is considered.

In the case of fixed and overtime labour the largest variations between stocking rates occur with the climate '0' scenarios where there are increases of 17 and 33 percent between the low and intermediate and low and high stocking rates. These compare with changes of -4 and +4 percent between the lowest and the intermediate and high stocking rates for the climate '1' scenarios. The pattern of changes in the demand for casual labour is somewhat different to fixed and overtime labour. Between the low and intermediate stocking rates there is no change in the demand for casual labour for climate '0', but there is a reduction of 8 percent for the climate '1' scenarios. Between the low and high stocking rates there are reductions of 50 and 23 percent for the climate '0' and '1' scenarios, respectively. As in the experiments reported in Sections 9.1 and 9.2, the pattern of results tends to be somewhat mixed and reflects the changes that are evident in cropping and cattle enterprises that occur on other farm types.

On the 'cattle and sheep' farms there is a tendency for labour requirements to increase with stocking rate and to decrease with a change in climate. Further the increases in labour requirements with increases in stocking rate tend to be greater for the current climate than for climate '1'. On this farm type the greatest requirement for labour involves the current climate and the highest stocking rate while the smallest requirements for labour involve the lowest stocking rate and climate '1'.

There is a small reduction in total labour requirements of 1 percent at the lowest stocking rate between climates '0' and '1'. At the intermediate and high stocking rates there are reductions in total labour requirements of 10 and 12 percent with a change in climate. A further point is that the declines in labour requirements with changes in climate tend to be greater for casual labour than for fixed and overtime labour. The reason for this is related to a reduction in the requirements for animal housing with a change in climate.

In the climate '0' scenarios there are increases in labour requirements between the lowest and intermediate stocking rates of approximately 11 percent and between the lowest and highest stocking rates of 13 percent. Further the increases appear to be distributed relatively evenly between fixed and overtime labour and casual labour. However, for the climate '1' scenarios there is little difference in the labour requirements for the different stocking rates. The variations in the labour requirements between the different stocking rates can largely be explained by changes in animal numbers.

In the case of 'dairy' farms there tend to be small reductions in total labour requirements with a change in climate. The decline in labour requirements principally involve reductions in casual labour as there are small increases in fixed and overtime labour with changes in climate. The extent of the reductions in total labour requirements with changes in climate range from 4 to 6 percent for the lowest and intermediate stocking rates, respectively. These compare with reductions in casual labour of 38 and 63 percent for the same stocking rates. A similar comparison of fixed and overtime labour shows an increase in labour requirements of approximately 1 percent. These results suggest that the reduced seasonality of forage production that occurs with altered climatic conditions allows 'dairy' farmers to substitute relatively cheaper full time labour for more expensive casual labour.

On 'dairy' farms there tend to be an increases in labour requirements with increases in stocking rate. For the climate '0' scenarios there are increases in the overall requirements for labour of approximately 1 and 5 percent between the low and intermediate stocking rates and between the low and high stocking rates, respectively. A similar comparison for the climate '1' scenarios shows a small reduction of 1 percent between the low and intermediate stocking rates and an increase of 4 percent between the low and high stocking rates.

The decline in the requirement for labour between the climate '1' scenarios that involve the low and intermediate stocking rates is mainly caused by a large reduction of approximately 44 percent in casual labour. This compares with a reduction of 7 percent in casual labour between the low and intermediate stocking rates and the climate '0' scenarios. Between the low and high stocking rates there are increases in casual labour for both climates '0' and '1' that range from 2 to 8 percent while increases in the requirements for fixed and overtime labour with increases in stocking rate range between 3 and 5 percent.

On 'sheep' farms total labour requirements tend to decline with changes in climate, and increase with stocking rate. In the case of changes in climate there are reductions in fixed and overtime labour that range from less than 1 percent to approximately 2 percent, while casual labour varies by -3 to +2 percent. The net effect of these changes are, therefore, small and range from -1.5 to -0.2 percent. With regard to variations between stocking rates the requirements for fixed and overtime labour increase by 3 to 5 percent and casual labour increase by between 0 and 7 percent between the lowest stocking rate and the intermediate and high stocking rates, respectively. These correspond to increases in overall labour requirements of 3 to 5 percent. The magnitude of these changes tends to be less than the differences in sheep numbers would suggest (see Table 9-13). However, much of the variability in sheep numbers occurs on 'cattle and sheep' farms so that animal numbers on 'sheep' farms are relatively less affected by changes in climate and stocking rates.

Of the various farm types 'cropping' farms, are the most affected by changes in climate and stocking rates. The greatest demand for labour occurs in the scenario that involves climate '0' and the intermediate stocking rate while the lowest labour demand involves climate '1' and the highest stocking rate. At the lowest stocking rate there is an increase in the overall demand for labour of approximately 12 percent with a change in climate. This compares with reductions in total labour requirements with changes in climate of 12 percent for the intermediate stocking rate and 21 percent for the high stocking rate. The changes in the demand for labour with changes in climate are the result of substitutions between fixed and overtime and casual labour. In the case of the lowest stocking rate a change in climate is accompanied by an increase in fixed and overtime labour and a decrease in casual labour. However, at the intermediate and high stocking rates climatic changes are associated with decreases in fixed and overtime labour and increases in casual labour.

Between the lowest and intermediate stocking rates there is an increase of 33 percent in overall labour requirements for the climate '0' scenarios. This compares with an increase of only 4 percent between the reduced and current stocking rates and the climate '1' scenarios. Between the low and high stocking rates there is an increase of 25 percent for the climate '0' scenarios and a decline of 12 percent for the climate '1' scenarios. The size of the changes in labour requirements with changes in stocking rates was initially surprising given that changes in animal numbers only indirectly affect 'cropping' farms. However, the pattern of crops that are planted and hence the demand for labour are strongly influenced by the requirements of livestock farms for feed grains and straw.

The last of the farm types to be considered are 'cropping and cattle' farms. On this farm type the largest requirement for labour is 0.20 m man days and involves climate

'0' and the highest stocking rate. In contrast the smallest demand for labour is 0.17 m man days and is associated with climate '0' and the lowest stocking rate. At the lowest stocking rate there is an increase in labour requirements with a change in climate of 15 percent. At other stocking rates there are small reductions in the demand for labour of between 2 and 4 percent with a change in climate. Further, at all stocking rates there are decreases in the demand for casual labour with changes in climate that range from 23 to 54 percent. These compare with increases of 27 and 4 percent in the requirements for fixed and overtime labour with changes in climate for the low and intermediate stocking rates, respectively. At the high stocking rate there is a small decline in the demand for fixed and overtime labour of 0.5 percent with a change in climate.

9.3.5 Financial Results.

The experimental results that refer to changes in the end of year financial status of farms are presented in Table 9-17 and Appendix 11-12. From Table 9-17 it can be seen that there tend to be reductions in the end of year cash position of farms with a change in climate. Further, there is a large difference between the financial outcomes associated with the low and intermediate stocking rates but there is only a small additional improvement between the intermediate and raised stocking rates. At the national level the final cash position of farms declines by 27 percent from £ 461.5 m to £ 336.0 m for the reduced stocking rate with a change in climate. This compares with declines between climates of 20 percent from £ 567.2 m to £ 453.7 m for the existing stocking rate and 21 percent from £ 579.9 m to £ 458.6 m for the increased stocking rate.

The above changes correspond to differences of +23 and +35 percent between the low and intermediate stocking rates for climates '0' and '1', respectively. These compare with much smaller increases of 2 and 1 percent between the intermediate and high stocking rates for climates '0' and '1', respectively. The results suggest that a change in climate has a similar effect to reducing the stocking rate by 15 percent from the current level. Also, although the financial position of some of the farm types declines with higher stocking rates it is likely that these farmers will elect to increase their stocking rates (at least to the levels indicated in the solution) as this represents their best option given the responses of other farmers. This contrasts with climate change which is likely to have a detrimental effect on the financial status of farms but is clearly not a variable that can be controlled by farmers.

Table 9-17. Results of Land Selling and Purchasing Experiments. End of Year Cash Position (£, 000,000's).

Animal Number =	-15 %		+0 %		+15 %	
Climate	'0'	'1'	'0'	'1'	'0'	'1'
'Cattle and sheep'	221.0	164.0	284.2	225.2	283.2	228.6
'Dairy'	111.7	88.6	142.0	118.4	145.7	108.0
'Sheep'	94.6	78.6	115.6	102.1	112.9	105.7
'Cropping'	21.3	0.0	0.0	0.0	21.3	9.6
'Cropping and cattle'	12.9	4.8	25.4	8.0	16.8	6.7
Scotland	461.5	336.0	567.2	453.7	579.9	458.6

With regard to the individual farm types there is a decline in the financial status of 'cattle and sheep' farms with a change in climate. The magnitude of these declines ranges from 26 percent for the lowest stocking rate to 19 percent for the highest stocking rate. On this farm type, therefore, an effect of increasing the stocking rate is to reduce the negative impact of a change in climate. Between the lowest and the intermediate stocking rates there are increases in the end of year cash position of 29 and 37 percent, for the current and altered climates, respectively. However, there is little difference in the financial status of this farm type between the intermediate and high stocking rates. The principle reason for this result is that the increased revenues obtained from the high stocking rate is largely offset by an increase in the average costs associated with feeding animals.

On 'dairy' farms there is a decline in financial status with a change in climate that ranges from 17 percent for the intermediate stocking rate to 26 percent for the highest stocking rate. With regard to stocking rates there are increases in the end of year financial status of approximately 30 percent between the low and intermediate stocking rates. However, between the intermediate and high stocking rates there is little difference in the climate '0' scenarios and a decline of approximately 9 percent for the climate '1' scenarios. For the climate '0' scenarios the highest end of year cash position is recorded for the high stocking rate while for the climate '1' scenarios the final cash position is highest at the intermediate stocking rate.

In the case of 'sheep' farms there is a decline in the end of year financial situation with a change in climate that ranges from 17 percent for the lowest stocking rate to 6 percent for the highest stocking rate. As with 'cattle and sheep' farms, therefore, an increase in the stocking rate has the effect of reducing the detrimental impact of a change in climate. Between the lowest and intermediate stocking rates there is an increase in the final cash position of farms of approximately 22 and 30 percent for climates '0' and '1', respectively. In contrast there is little difference between the intermediate and high stocking rates.

On 'cropping' farms the most prominent feature of the results is that the final cash position falls to zero for the treatment involving the lowest stocking rate and climate '1' and for the intermediate stocking rates. Also at the high stocking rate there is a decline in the end of year cash position with a change in climate of 55 percent. These results contrast with the base runs and the sensitivity analysis where there are increases in the final cash position with a change in climate. The results also appear to be in conflict with the outcomes associated with land sales and purchases as 'cropping' farms are a net purchaser of land. The increase in the size of 'cropping' farms suggests that revenues should also increase, however, the results show a decline in the income of this farm type compared with the base runs.

This result only becomes explicable when the production and transport of feed grains and hay are considered. In this experiment, considerably larger volumes of feed barley, feed wheat and hay are transported between farms and regions than in either the base runs or the sensitivity analysis. The reason that this is important is that the model does not expressly account for the exchange of cash when selling or purchasing intermediate goods between farm types or regions. Rather the model determines the value and hence the volume of hay and feed grains that are exchanged between farm types and regions (see Section 4.1). If the value of these exchanges is incorporated into the estimated cash transactions then the pattern of changes in the financial situation of 'cropping' farms with changes in climate is similar to that found in the base runs.

On 'cropping and cattle' farms the highest financial result is associated with the intermediate stocking rate and the lowest financial result involves the reduced stocking rate. The magnitude of the increases in the final cash position between the lowest and intermediate stocking rates are 97 and 67 percent for climates '0' and '1', respectively. This compares with declines of 34 and 16 percent between the intermediate and high stocking rates. With regard to differences between climates there are declines in the final cash position of farms that range from 68 percent for the intermediate stocking rate to 60 percent for the highest stocking rate.

The size of the responses on the 'cropping and cattle' farms to changes in climate are greater than in the base runs. Also, the relative response to stocking rate is larger than for other farm types that involve animal activities. A factor that contributes to this result is related to the transfer of intermediate goods between farm types and regions. As discussed above the cash value of feed grains and hay that are produced and sold by 'cropping and cattle' farms are not explicitly accounted for in the model. However, if the cash value of intermediate goods were included in the model then the responses to changes in climate and stocking rates would tend to be lower than the current levels. The reason for this is that the volume of transfers in intermediate goods tend to be greater with changes in climate and also at higher stocking rates.

9.4 Summary.

In the first part of this chapter the results of the base runs are presented. The purpose of this experiment was to provide a basis for comparison with subsequent runs with the model and to consider the types of short term adjustments that farmers make in response to climatic change. In these runs the constraints that relate to the amount of land, the starting cash position and repayments of long term debts, the maximum amount of casual labour and numbers of breeding stock that are associated with each of the farm types and regions are maintained at 1995 levels (see Appendix 3). The only variables in the model to be varied between the scenarios, that represent climates '0', '1' and '2', are the coefficients that relate to the potential growth of cash and forage crops (see Section 5.2.2), the coefficients that relate to soil nitrogen (see Section 5.3.6), and the estimates of workable hours (see Section 7.1.1).

There are no differences between climates '0', '1' and '2' in terms of beef and dairy animal numbers, and only very small differences (less than 0.5 percent) in the production of meat and milk. In all three scenarios, beef and dairy numbers correspond to the maximums that are associated with each of the farm types and regions. However, in the case of sheep there is a decline in ewe numbers and an associated reduction in lamb production with a change in climate. Although there is little difference between the climate change scenarios (climates '1' and '2') in terms of the extent of national reductions in sheep production, there are differences in regional sensitivities, that vary depending on which of the climate change scenarios is being considered.

Although the areas and yields of grass and grass / clover vary with changes in climate, there is little difference between any of the climatic scenarios in total forage production. However, there are differences between the climates in the seasonal pattern of forage production. In the case of the climate scenarios '1' and '2', spring and summer production tends to be higher and autumn production is lower, than for the current climate. The reduction in autumn forage production is the principle cause for the decline in sheep numbers with changes in climate.

In terms of the arable crops there is an increase in the average yield of spring barley, winter wheat, potatoes and vining peas and a decrease in the average yield of winter barley and oilseed rape with a change in climate. However, the net effect of the variations in yields and areas results in a decline in the production of cereal crops with changes in climate. In the case of potatoes an increase in yield is compounded by an increase in area so that the national crop increases by between 25 and 35 percent with a change in climate. For vining peas the increase in per hectare productivity tends to be offset by reductions in planted area so that there is a small reduction in total production between climates '0' and '1' whereas there is a small increase between climates '0' and '2'. In the case of oilseed rape, there is a reduction in both per hectare productivity and planted area.

There tend to be decreases in labour requirements on farms that involve livestock (with the exception of 'cropping and cattle' farms) and increases on 'cropping', and 'cropping and cattle' farms with changes in climate. On livestock farms these declines are the result of reductions in the requirements for animal housing and sheep numbers. On the 'cropping', and 'cropping and cattle' farms the increases in labour requirements with changes in climate are the result of increases in labour intensive crops such as potatoes and the increases in the average per hectare labour requirements of individual crops. The reason for the increases in the average requirements of crops is related to the increase in workable hours that occur with changes in climate: that is farmers utilise the additional time by using smaller machines and making less use of contracting services.

There is a decline in the aggregate financial status of Scottish farms of approximately 20 percent between climates '0' and '1', and a decline of approximately 25 percent between climates '0' and '2'. However, the extent of these changes is not consistent across either regions or farm types. If the regional changes in financial status are considered, there are declines in all regions with changes in climate. Paisley is the most affected while Kinloss and Wick are moderately affected with Mylnefield being the least affected. The percentage declines in the financial status of the farm types with changes in climate are similar for 'cattle and sheep', 'dairy', and 'sheep' farms and contrast with improvements in the status of 'cropping' farms, while 'cropping and cattle' farms remain relatively unaffected. To a large extent the variations in the regional sensitivities to climatic change can explained by differences in the relative numbers of the farm types that comprise the individual regions. That is in relative terms Mylnefield has the most 'cropping' farms, and is therefore relatively less affected by declines on livestock farms, than the other regions.

The sensitivity analysis that is performed with the model involved investigating the robustness of farming systems that rely on the sale of cash crops versus those that are reliant on livestock. As in the base runs, the numbers and productivity's of beef and dairy cattle only varied by a small amount, less than 0.5 percent, with changes in climate. Further, there are no variations in the numbers of beef and dairy animals with the changes that are imposed on the yield of either cash or forage crops. Also, as in the base runs, there are declines in sheep numbers with changes in climate. Although sheep numbers did not appear to be sensitive to the treatments that involved altering the yield of cash crops, the responses to variations in the yield of forage crops are similar in magnitude to a change in climate.

In the experiments that involve varying the yield of cash crops the variations in the total production of forage that arise with changes in climate tend to be cancelled out by compensating changes in the areas and productivity's of grass and grass / clover. In the experiments where the yield of forage crops is altered, although there is little difference between climates, there is a difference in total forage production between the treatments that involve an increase versus a decrease in potential productivity. To some extent, an increase in the productivity of forage reduces the dependency of livestock farms on feed grains that are produced by 'cropping' farms. However, as observed in the base runs, variations in the timing of forage production that occur with changes in climate are critical both in terms of the numbers of animals that are carried and the transfer of feed grains between farms.

There is a reduction in the total production of cereal crops with a change in climate. Further, the declines in cereal production with changes in the yield of cash and forage crops tend to less for the climate '0' scenarios than for the climate '1' scenarios. At least some of the reduction in cereal production that occurs in response to climate change is related to the decline in the requirements for feed grains on livestock farms. In the case of potatoes there is a large increase in both area and yield in response to a change in climate but only small changes are due to variations in the yield of cash and forage crops. This contrasts with vining peas which are more sensitive to climate than to the changes imposed on the yield of cash and forage crops. The situation with respect to oilseed rape is for production to decline with changes in climate but to increase from the experiment that involves a decrease in the yield of cash crops and other experiments where the yield of crops is varied.

In the sensitivity analysis, the variations in labour requirements with changes in climate are similar to the base runs. There is a decrease in labour requirements on livestock farms (excluding 'cropping and cattle' farms) with a change in climate and an increase in requirements on farms that involve cropping operations. Further, there are increases in the demand for fixed and overtime labour and reductions in the demand for casual labour with changes in climate. This occurs as the seasonality of labour demands tend to be lower with changes in climate so that relatively expensive casual labour can be substituted for by fixed and overtime labour. Also, there tend to be increases in labour requirements with increases in the yield of cash and forage crops.

In terms of changes in the financial status at the national level there is a decline in the final cash position of farms with a change in climate. Further, the pattern of changes in the financial position of individual farm types with changes in climate are similar to those found in the base runs. In the treatments where the yield of crops is altered, there is relatively little difference between cash or forage crops, in terms of their influence on the aggregate financial position of Scottish farms. For a given climate, therefore, an increase in the yield of cash crops has a similar effect to an increase in the yield of forage crops.

This result was contrary to expectations as livestock account for a much larger proportion of Scottish agriculture than cropping. This result is related to the higher profitability of 'cropping' farms compared with livestock operations. Also, because of the maximum constraints on the numbers of breeding animals and issues associated with the timing of feed demands by animals (for further discussion, see Chapter 10), livestock farms are not well positioned to utilise additional feed that arises with changes in climate or from increases in the potential yield of forage crops. The results of the sensitivity analysis tend to confirm the outcomes of the base runs in that 'cropping' farms stand to gain the most from a change in climate while 'sheep' farms are likely to lose the most.

In the third section of this chapter, there is an evaluation of long term adjustments in farming systems. In this experiment, the purchase and sale of land is considered and the maximum numbers of livestock that can be carried on the different farm types is allowed to vary. Although the assumptions that are associated with the experiment involve a significant simplification of reality, the experiment should provide an indication of the types of structural adjustments that are likely to occur on Scottish farms.

With respect to the sale and purchase of land, there are transfers of land from 'cattle and sheep', 'dairy' and 'sheep' farms to 'cropping', and 'cropping and cattle' farms. Further the amount of land that is transferred tends to be greater for climate '1' than for climate '0'. In the climate '0' scenarios the amount of land that is transferred is lower for the high and low stocking rates than for the existing stocking rate. This contrasts with the climate '1' scenarios where land transfers are highest for the lowest and highest stocking rates. Of the various treatments the largest transfer of land occurs for the climate '1' scenario and the lowest stocking rate. Further, the largest transfers of land occur at Kinloss, while at Wick there are no purchases or sales of land. At Paisley and Mylnefield the transfers of land are intermediate to those at Kinloss and Wick.

Of the various types of livestock, sheep are the most sensitive to a change in climate. There is a tendency for ewe numbers to decline, with changes in climate, in the majority of regions and stocking rates. With regard to beef cattle, animal numbers are constrained by the maximum limits on stocking rate at the low and intermediate stocking rate. However, there is little difference between the intermediate and high stocking rates in terms of the numbers and productivity's of beef animals. In contrast, in all of the experimental treatments the numbers of dairy cattle are close to the maximum numbers allowed in the solution. As a further point, the numbers of beef and dairy animals do not appear to be sensitive to changes in climate. The results reflect the fact that sheep are the least profitable of the modelled livestock types while dairy animals are the most profitable.

In terms of the areas and productivity's of grass and grass / clover there is little difference between stocking rates or climates in the total amount of forage that is produced. This contrasts with the cereal crops where there is an increase in total production for the climate '0' scenario with an increase in stocking rate. This compares with the climate '1' scenario where there is a decline in production with increases in stocking rates.

There is a tendency amongst the remaining crops for areas to decline with changes in climate. If the effect of stocking rate is considered, there tend to be increases in the total area of potatoes, vining peas, and oilseed rape between the low and intermediate stocking rates and also between the low and high stocking rates. The mechanism by which changes in stocking rates affect the activities of 'cropping' farms is related to the requirements of animals for feed grains and straw. From the preceding results it can be seen that the changes that occur on livestock farms can have a considerable impact on 'cropping' farms.

The total labour requirements for Scotland tend to be greatest at the intermediate stocking rate. Further, there is a tendency for labour requirements to be more variable with changes in stocking rate for the climate '0' scenarios than for the climate '1' scenarios. The pattern of changes in labour requirements that emerges with changes in climate depends both on the farm type and the stocking rate that is considered. In the case of livestock farms (excluding 'cropping and cattle' farms) labour requirements tend to increase with stocking rate and to decrease with changes in climate. On these farm types the changes in labour requirements tend to reflect differences in the requirements for housing and forage conservation.

Of the various farm types, labour use on 'cropping' farms are the most sensitive to changes in climate and stocking rates. The largest requirements for labour occur in the scenario that involves the intermediate stocking rate and climate '0' while the smallest demand occurs with the highest stocking rate and climate '1'. A partial explanation for these variations is related to changes in the demand for feed grains. This is because the labour requirements that are associated with producing feed grains are relatively low compared with other crops. The higher the demand for feed grains, therefore, the lower the requirement for labour on farms that produce this grain. In the case of 'cropping and cattle' farms, the pattern of changes in labour requirements with changes in climate and stocking rates is somewhat mixed and reflects the divergent changes in the livestock and cropping activities that comprise the farm.

In terms of the financial results, at the national level there is a tendency for the final cash position of farms to decline with a change in climate. Further, there is a large increase in financial status between the lowest and intermediate stocking rates but only a small additional gain is obtained between the intermediate and high stocking rates. The results are complicated, however, by the fact that the value of transfers of feed grains and straw between cropping and livestock farms are not reported. For this reason the income of cropping farms, and the expenditure of livestock farms, are understated. If the financial value of these transactions is taken into account, then the changes in the financial status of the farm types with changes in climate are similar to those found in the base runs and in the sensitivity analysis. That is a change in climate results in a decline in the financial status of livestock farms but on cropping farms there is an improvement in the financial position with a change in climate.

10. SUMMARY AND CONCLUSIONS.

Recent evidence relating to the build up of greenhouse gases in the atmosphere has caused concern amongst the scientific community about the possibility of global climate change and the impacts that these changes may have on the environment and agriculture. The potential importance to the global economy has resulted in a considerable amount of international political activity being focused on issues associated with climate change. Further, the complexity of the methodological and data-related issues that are involved, is reflected by the large number of research programmes currently analysing and modelling the implications of climatic change. One area of concern is the impact that changes in climate will have on the regional and national patterns of cropping and animal production, and hence the structure of farming systems.

In any study of an economic system, decisions must be made as to the level of resolution or detail to be considered, as there are inevitably trade-offs between aggregation and data errors. That is, the more disaggregated a model the greater the errors that are involved with collecting and representing data but the lower the aggregation errors. Another way of looking at this issue is that it is generally easier to represent the existing status of a system by using a highly aggregated model but this may be at the cost of it being more difficult to accurately mimic the effects of a perturbation to that system.

The choice as to the most appropriate level of aggregation of the model should be related to the nature of the problem and to the objectives of the research. With respect to this study, an important consideration was that climatic change is likely to occur in the future when economic conditions and the structure of the agricultural industry will be different from today. The inclusion in the model of aggregate relationships, that are based on past experience, is therefore of limited value. In terms of the objectives of this research the principle aim of the study was to evaluate the possible effects of a change in climate on the pattern, structure and viability of agriculture in Scotland. To address this objective it was necessary to develop an approach for studying the effects of climate change at various levels of resolution, that is at farm, region and national levels.

One of the tenets of this study is that it was possible to construct relatively simple models that can be used to represent the behaviour of complex systems. Further, that the predictive performance of a model is greater if it is based on mechanistic relationships between the biological, physical and economic components of the system (Bywater, 1990). The current study endeavoured to incorporate these ideas within a mathematical modelling framework. It is argued that this study has been successful in developing a LP model that is useful for studying a highly complex problem.

The LP model includes a large amount of biological, physical and economic detail. The inclusion of this information allowed the types of adjustments that farmers are likely to implement to be considered. The interactions between farmers in terms of flows of intermediate goods, land, and labour is considered in the national level model, so that the model could be used to evaluate changes in the relative importance of different farming systems and also the spatial distribution of production. The process of systematically integrating information from a wide range of different sources into a national level model was of considerable utility for analysing the complex issues that relate to climate change.

The estimation of most of the parameters in the enterprise models was relatively straightforward, particularly when there was a reasonable degree of similarity between the structure of the enterprise models and the simulation models on which they were based. However, in other cases, the restrictions associated with LP, such as the difficulties involved with including non-linear responses or the smaller number of time periods that can be represented compared with simulation models (see for example Hazell and Norton, 1986), limited the ability of the enterprise model to reproduce the predictions of the simulation models. It was important therefore to establish a detailed understanding of the performance of the LP models versus the simulation models for the range of conditions likely to be encountered in the experiments with the model. It should be noted, however, that in spite of these difficulties the model evaluation (see Chapter 8) showed an acceptable level of agreement between the LP models and the simulation models.

Another difficulty associated with using suites of simulation models is that are usually constructed with differing objectives so that the models account for different sources of variation. An example in this context is that the simulation models used for barley, peas, and oilseed rape did not account for nitrogen limitations to crop growth. In order to standardise the forms of variation that were accounted for it was necessary to collect data that could be used to estimate parameters in the LP models for situations where the simulation models did not provide suitable information.

Also, the histories of the simulation models are often different so that prior validation may have occurred for situations where the location or management conditions were different to those required. For example, there has been little work in Britain to model either pea or oilseed rape growth; the model that was selected to represent these crops was developed in Sweden (Kvifte, 1987) and adopted much simpler assumptions with regard to crop development than the wheat and potato models that are used in this study. Although Kvifte's model was validated as part of this study the relative simplicity of the model meant that considerable care was necessary when predicting changes in crop growth for the conditions considered in this study.

As a further point, the decision to include relatively detailed relationships within the model has not been without cost. The implications for the size of the model and issues associated with data acquisition have been significant. Because of the size of the model there were considerable difficulties involved in the verification and validation of the model. Another difficulty that arose was in interpreting large quantities of model output. The size of the experiment performed in this analysis presented problems in eliminating errors from the input and ensuring that the model results were sensible. Simplification of the study would allow a larger proportion of limited time resources to be devoted specifically to the problem in question, rather than as occurred here, to necessary but not directly productive uses.

To an extent, perhaps, the model has erred towards providing too much detail on certain issues while ideally other factors should have been represented in greater detail. For example, the methods used to represent crop responses to nitrogen and pesticides could have been simplified. The principle reason for representing nitrogen and pesticides in the model is that responses to these factors are of concern to farmers whose application strategies may vary with changes in climate. Although the validation results showed that the model performed well in terms of predicting variations in crop yields at differing rates of nitrogen use, the single year time horizon of the model and restricted set of soil types that are represented, meant that relatively little useful information was derived from this part of the model.

This is because the experiments are based on yearly averages and in most cases nitrogen and pesticides are applied at the maximum permissible rates. If the structure of the model was altered to include a multiple year time horizon and possibly a wider range of soil types, the inclusion of nitrogen and pesticide responses may have been of more direct value. The retention of the nitrogen and pesticide components of the model is justified, however, by the fact that updates to the model structure that allowed better use of this part of the model should, excepting the implications for model size, be relatively straightforward to implement. Also, these components could be used in other models in the future.

The model may also be better suited to studies that explicitly consider adjustments in farming practices through time if the time horizon of the model was extended. This would improve the ability of the model to address issues relating to the temporal effects of farm expenditure on capital items, and make the model better suited to analyses where it is not appropriate to assume that farms have achieved a steady state in response to a change in environmental conditions. This improvement would come at some cost in terms of model size and computational requirements, but this should not represent an insuperable obstacle as the Dantzig-Wolfe formulation provides considerable flexibility in terms of the size of model that can be solved.

Some other issues that may warrant attention if the model is used in a future study relate to including a more detailed representation of agricultural policy instruments and also to revisit the farm typology that is presented in this study. The Common Agricultural Policy (CAP) of the European Union (EU) has a considerable impact on agriculture but was only partially represented in this study. The approach taken was to include the effects of the CAP in terms of average price levels for produce and also to incorporate direct payments that are made for livestock and crop areas. However, no attempt was made to include the restrictions that are placed on payments such as quotas, and headage and area limits. Although there should not be any significant difficulties in including such limits neither would the data requirements or implications to the model structure be trivial. In this study the principle focus has been on the bio-physical aspects of production, however, the economic impacts of the CAP are important and this is an area that might be addressed if the model is used in the future.

There are several reasons that the farm typology was established. Not least is that the ability to evaluate changes in farm status is critical to understanding changes in the pattern, structure and viability of agriculture in Scotland. It was considered essential, therefore, to provide a picture of the farm organisation and also provide a more global view of the response of farmers within a regional and national context. The farm typology was designed to minimise, as far as possible, the presence of aggregation bias in the regional model. Norton (1995) suggests that proportionality of resource endowments is probably the most important of Day's criteria for ensuring that aggregation bias is minimised (Day, 1963a and 1963b). Hazell and Norton (1986) consider that Day's criteria are demanding and suggest that providing the representative farms have similar resource endowments, yields and access to technology, that this should be sufficient for aggregation bias to be reduced to an acceptable level.

The factors that are used to differentiate the farm types include the proportion of income derived from milk, cattle, sheep and cropping, and also variables that relate to the available water holding capacity (AWC) of the soils on the respective farms, the farm business size, and whether or not the farm is sited in a less favoured area. The farm typology, therefore, includes a mix of input and output variables that reflect its current operations and also the ability of the farms to alter their operations in response to a change in climate. It should be noted, however, that the factors that limit a farmers ability to alter their operations may not be completely captured in the typology. For example the ability of hill and upland farmers to alter their pattern of land use is likely to be restricted by factors such as remoteness, lack of infrastructure, availability of labour, and land aspect and altitude. Further, as discussed in Section 3.2.1, the method of using AWC to represent differences in soil capability was not entirely satisfactory.

In any cluster analysis, compromises must be made in terms of the number of factors that are used and also the number of groups that are selected. Although the typology appeared to be reasonable in terms of providing farm groups that are broadly similar to expectations and to the SOAEFD farm typology (see Section 3.1), the relative simplicity of the typology reduces the model's ability to represent the trade in store animals between farms. While the flows of hay and feed grains and also competition for labour and contracting services between farm types are modelled the absence of explicit linkages to represent the trade of store livestock is a shortcoming that, in conjunction with the farm typology, could be reviewed as part of a future study.

In terms of the individual farm type models the majority of effort was directed towards modelling cropping systems and pasture as these are directly affected by changes in climate (see Chapter 6). For this reason a large amount of information was included in the models to represent variations in the growth and development of cash and forage crops. Also, the management of crops on different soils in terms of variations in planting dates, rotations, use of nitrogen and pesticides and machinery complements to perform various tasks is modelled in considerable detail.

In comparison livestock operations are modelled in much less detail. The feeding and growth of animals is handled in a flexible manner in terms of the model being able to select between grass and grass / clover and from a range of purchased feed stuffs and hay and silage. There is also flexibility in the model to allow animals to be brought to market at different times, however, the options that farmers have to alter the profile of animal requirements, through actions such as altering the timing of lambing and calving or adopting different strategies for buying or selling livestock, is comparatively restricted. The detrimental effects that were observed in the preceding chapter may, therefore, have been lower or even reversed if the model was structured to allow livestock demands to be better synchronised with changes in the pattern of forage production. Further, at least in principle, these types of changes would not be difficult to include as the livestock models only account for a very small proportion of the model structure.

A number of other possibilities with regard to the future use of the model can be suggested. These include relaxing assumptions relating to prices of agricultural inputs and outputs. The model currently estimates mutually consistent prices for intermediate goods that are transferred between farms, but it is assumed that these are influenced by exogenously determined prices imposed at the national boundary. While it would be possible to increase the generality of the model, by representing components such as the rest of the world, and suppliers of inputs and consumers of final outputs, so that prices for finished goods and for goods traded with the rest of the world could be endogenised at the Scottish border, this would be quite a large undertaking both in terms of data acquisition and the implications for the models structure.

Another issue that may warrant consideration relates to technological change. The comprehensive evaluation of issues relating to technology presents a complex task, as technologies tend to be specific to a particular agricultural production system, location and climate, so that if the climate changes then the value of a technology will also change. The model is relatively general in terms of the issues that can be addressed and while it is unlikely that there will be any significant impediments to evaluating the influence of factors such as technological change or risk the inclusion of additional factors in the model structure, needs to be carefully considered with regard to the implications that such changes may have on the ability of the model to address other study objectives.

While further developments to the model would allow the status of Scottish agriculture to be more accurately modelled, in its current stage of development, the model has allowed a realistic evaluation of the effects of climate change to be performed. On the basis of the models results, climate change is likely to have a detrimental effect on the profitability of Scottish agriculture. Further, the decline in the net income of Scottish farms with a change in climate is likely to be in the order of 20 percent.

In general there is a decline in the net income of livestock farms, with a change in climate, with 'sheep' being particularly affected. In contrast, the income of 'cattle and cropping' farms are relatively stable with changes in climate as increases in the income from crops tend to offset the declines associated with livestock enterprises. This compares with 'cropping' farms where the financial position should increase with a change in climate by approximately 40 percent. However, because 'cropping' farms are relatively few in number compared to livestock farms the changes that are observed at the national level tend to be dominated by livestock.

Although there are changes in the areas of both grass and grass / clover, these changes tend to be compensatory, so there is relatively little difference between the climatic scenarios in the total area or total production of forage. However, there are differences in the seasonal pattern of forage production with higher production being recorded in spring and summer and lower production occurring in autumn under the climate change scenarios. Also, there is an increased reliance on purchased feedstuffs and conserved forage on livestock farms with changes in climate. This occurs as a change in climate reduces the degree of synchronicity between the supply and demand for forage, and along with changes in sheep numbers, is the principle reason for the decline in the financial position of livestock farms.

Although there is an increase in the per hectare productivity of cereal crops with changes in climate this tends to be accompanied by a decline in total production as cereal crops are displaced by other crops that become relatively more profitable under different climatic conditions. Of the arable crops that benefit from a change in climate the principle increase in both area and per hectare productivity occurs with potatoes.

In the base runs (see Section 9.1) there is an increase of approximately 25 percent, between climates '0' and '1', in total potato production.

The trends in the total labour requirements with climate change are similar to the changes in the profitability of the different farm types. That is labour requirements tend to increase on cropping farms and decrease on livestock farms with changes in climate. There are two reasons for the increases in labour requirements on cropping farms with changes in climate. The first is related to the substitution of less labour intensive crops (for example cereals) by crops that require greater amounts of labour (for example potatoes). The second reason is that there is an increase in workable hours with a change in climate so that farmers are able to take more time to perform tasks by using smaller machinery and also by making less use of contracting services. With regard to livestock farms the declines in labour requirements with a change in climate are related to the declines in sheep numbers and also to the reduced requirements for animal housing.

The changes in the pattern of production that are discussed above principally relate to the changes that were observed in the base runs (see Section 9.1). Although the patterns of changes in the base runs were broadly similar to those found in the sensitivity analysis (see Section 9.2) the complexity of the responses to climatic change tended be greater in the analysis of long term adjustments in farming practices (see Section 9.3). In the analysis of long term adjustments in farming systems the maximum numbers of livestock that can be carried was varied and the sale and purchase of land was permitted. As a result there was a change in the relative balance of the farming systems with cropping farms tending to expand at the expense of livestock farms. Further, the magnitude of these adjustments, as well as the trade in feed grains, tended to be greater for the climate change scenarios than for the existing climate. The interactions between the various farm types in terms of trade in feed grains, straw, and conserved forage had a large impact on the results of this experiment.

As a final point, this study has provided a framework for the successful analysis of climatic change at the national level in Scotland. The methodology that has been presented is transparent and could be transferred to other geographical areas. Further, the results have shown that although benefits can arise from climatic change, substantial welfare shifts may occur between different sectors of the Scottish agricultural industry.

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APPENDICES.

Appendix 1. Covering Letter Sent to Farm Accounts Scheme Farmers.

Dear Farm Accounts Scheme Co-operator,

GLOBAL WARMING

I am sure you will be aware of the concern being expressed with regard to global warming and what this may mean for Scottish farming in the years that lie ahead. Colleagues, based in Edinburgh, are engaged in a research programme which is trying to model the possible effects of changing climatic factors such as temperature and rainfall. They have reached the stage in which it would be be very useful if they could relate their knowledge of climate and soil types to actual physical data. We clearly hold a vast amount of relevant data in the Farm Accounts Scheme if it could be matched up with the various soil types, gradients etc., which contributed to the financial performance we already know.

I am writing to ask if you could be kind enough to further this research work by giving us an outline of your farm business as costed in the Farm Accounts Scheme. We have done some homework which has resulted in the enclosed map which we hope covers your farm. Could you please outline the farm boundary and return the map to us in the envelope provided. The research team will then 'digitise' the farm area, which will allow appropriate computer programs to overlay the various soil types and and climatic data. If the map is not quite covering the correct area, pleas attach an extra sheet of paper and draw in the approximate missing bit to the same scale (extending the grid lines might be helpful where appropriate). If we have got it totally wrong we will of course rovide you with another map.

I re-emphasise the importance that we attach to confidentiality and assure you that it will not be possible to trace data back to individual businesses in any published report that results from the global warming study. If you would rather opt out of this extra request, please return the map suitably annotated.

Thank you very much for your assistance with this very important project which could so obviously affect us all.

Yours sincerely

Appendix 2. Mean Soil Available Holding Capacity of Scottish Soils (mm)[1] .

Association	AWC	Association	AWC	Association	AWC
Aberlour	50.5	Elgin	76.9	Nigg	65.1
Alluvial soil	88.3	Ettrick	78.0	North Mormond	77.3
Ardvanie	91.5	Fleet	96.0	Not classified	111.9
Arkaig	63.3	Forfar	91.5	Ordley	92.0
Arran	92.0	Foudland	78.9	Orton	78.5
Ashgrove	125.4	Fraserburgh	60.32	Panbride	66.2
Auchenblae	67.4	Giffnock	85.7	Peat	25.5
Auchinleck	88.9	Glenalmond	93.2	Peterhead	93.0
Balig	38.8	Gleneagles	62.7	Pow	104.6
Balrownie	91.6	Gourdie	103.2	Preston	63.2
Bargour	89.0	Gruline	42.5	Reinstated soil	81.9
Barncorkrie	64.4	Hatton	73.3	Rhins	85.4
Bemerside	83.4	Hayfield	85.5	Rowanhill	96.3
Berriedale	68.4	Hindsward	82.5	Sabhail	87.1
Biel	118.1	Hobkirk	96.3	Saltings	111.3
Blair	59.2	Holywood	62.1	Skelmuir	74.4
Boyndie	75.9	Inchkenneth	87.3	Smailholm	91.8
Braemore	88.8	Inchnadamph	90.7	Sorn	93.8
Cairncross	81.5	Innerwick	80.6	Sourhope	75.7
Callander	88.5	Insch	88.2	Staffin	85.3
Canisbay	83.2	Kessock	42.4	Stirling	112.4
Canonbie	101.2	Kilmarnock	97.7	Stonehaven	91.3
Carbrook	99.0	Kindeace	68.0	Strathfinella	105.8
Carpow	92.8	Kintyre	79.7	Strichen	76.9
Carter	86.7	Kippen	90.3	Symington	66.9
Collieston	67.7	Kirktonmoor	91.9	Tarves	87.9
Corby	57.2	Kirkwood	81.9	Thurso	83.8
Countesswells	72.7	Knockando	135.7	Tipperty	110.5
Creetown	36.3	Knockskae	47.0	Tomintoul	74.8
Cromarty	89.6	Lanfine	73.8	Torosay	80.9
Cuminestown	73.6	Lauder	92.1	Torridon	57.0
Dalbeattie	70.8	Laurencekirk	87.5	Tynehead	65.1
Darleith	85.1	Leslie	62.6	Tynet	77.8
Darvel	65.4	Links	59.5	Wallis	51.0
Deecastle	89.3	Lochinver	65.4	Whitsome	103.2
Doune	69.2	Lynedardy	106.5	Yarrow	64.0
Dreghorn	83.9	Made up ground	108.6		
Drongan	99.8	Mauchline	67.9		
Dulsie	68.7	Millbuie	72.4		
Durnhill	55.8	Minto	106.5		
Eckford	64.2	Mountboy	88.0		

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[1] Source: Scottish Soils Database MacDonald *pers comm* (1995).

Appendix 3.1 RHS Coefficients: Area of Farm Types by Region and Land Class.

Farm Type	Land Class	Region			
		Kinloss	Mylnefield	Paisley	Wick
‘Cattle and sheep’	‘1’	260100	196500	372000	151200
	‘2’	558600	422100	798900	324900
	‘3’	603000	455700	862500	350700
	‘4’	128100	96600	183000	74400
‘Dairy’	‘1’	11100	6300	61200	3900
	‘2’	26100	14700	142800	9300
	‘3’	28200	16200	155100	10200
	‘4’	24900	14400	137400	9000
‘Sheep’	‘1’	40200	73800	234600	73800
	‘2’	82200	150600	479400	150600
	‘3’	37500	69000	219600	69000
	‘4’	9600	17400	55800	17400
‘Cropping’	‘1’	7200	24900	1800	0
	‘2’	27300	96000	6900	0
	‘3’	54000	189300	13500	0
	‘4’	36000	125400	9000	0
‘Cropping and cattle’	‘1’	5400	9900	1800	0
	‘2’	21900	40200	7200	0
	‘3’	33300	60900	11100	0
	‘4’	31200	57300	10500	0

Appendix 3.2 RHS Coefficients: Financial Status.

	Farm Type	Region			
		Kinloss	Mylnefield	Paisley	Wick
Cash at Start of Year (£ 000's)	'Cattle and sheep'	21699	16398	31032	12615
	'Dairy'	4185	2388	23007	1494
	'Sheep'	3156	5784	18408	5784
	'Cropping'	4020	14073	1005	0
	'Cropping and cattle'	657	1206	219	0
Net Repayments of Fixed Debt[1] (£ 000's)	'Cattle and sheep'	22722	17172	32499	13209
	'Dairy'	5712	3261	31413	2040
	'Sheep'	699	1284	4086	1284
	'Cropping'	7887	27609	1971	0
	'Cropping and cattle'	4701	8622	1566	0

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[1] The estimates included here refer to annual net payments of fixed debt. In the model these payments are made on quarterly basis.

Appendix 3.3 RHS Coefficients: - Maximum Casual Labour.
- Capital Livestock.

	Farm Type	Region			
		Kinloss	Mylnefield	Paisley	Wick
Maximum Casual Labour (man days, 000's)	'Cattle and sheep'	44	32	63	25
	'Dairy'	10	7	59	3
	'Sheep'	5	12	36	12
	'Cropping'	50	179	14	0
	'Cropping and cattle'	9	15	2	0
Number of Cattle (head)	'Cattle and sheep'	113208	85346	161842	66000
	'Dairy'	0	0	0	0
	'Sheep'	0	0	0	0
	'Cropping'	0	0	0	0
	'Cropping and cattle'	12792	23654	4158	0
Number of Dairy Cows (head)	'Cattle and sheep'	0	0	0	0
	'Dairy'	33000	19000	180000	12000
	'Sheep'	0	0	0	0
	'Cropping'	0	0	0	0
	'Cropping and cattle'	0	0	0	0
Number of Sheep (head)	'Cattle and sheep'	847585	641076	1212629	493334
	'Dairy'	0	0	0	0
	'Sheep'	132415	242924	772371	242666
	'Cropping'	0	0	0	0
	'Cropping and cattle'	0	0	0	0

Appendix 4.1 Machinery Costs.

		Section[2]	Work Rate (hectares / hour)	Minimum Tractor Required	a) Purchase Price (£)	b) Opportunity Cost of Capital (£ / month)[3]	c) Sinking Fund (£ / month)[2]	d) Road Fund License and Insurance (£ / month)[4]	f) Total Monthly Payments (b + c + d) (£ / month)	Running Costs that vary with Machine Usage[5] (£ / hour)
Wheeled	1	2.1.5	n.a.	n.a.	23000	258.8	91.5	25.5	375.8	1.8
Tractor[6]	2	2.1.4	n.a.	n.a.	19500	219.4	77.6	22.0	319.0	1.5
	3	2.1.3	n.a.	n.a.	15000	168.8	59.7	17.5	246.0	1.2
Plough	1	3.1.3	0.7	1	6500	73.1	25.9	2.2	101.2	2.2
	2	3.1.2	0.6	2	4250	47.8	16.9	1.4	66.1	1.4
	3	3.1.1	0.5	3	2500	28.1	9.9	0.8	38.8	0.8
Roller	1	3.9.3	3.2	1	14000	157.5	55.7	4.7	217.9	2.1
	2	3.9.2	2.4	2	6000	67.5	23.9	2.0	93.4	0.9
	3	3.9.1	2.0	3	2000	22.5	8.0	0.7	31.2	0.3
Light Dutch	1	3.8.3	4.0	1	6000	67.5	23.9	2.0	93.4	2.1
Harrows	2	3.8.2	3.2	2	4000	45.0	15.9	1.3	62.2	1.4
	3	3.8.1	2.4	3	1250	14.1	5.0	0.4	19.5	0.4
Conventional	1	4.1.3	3.0	1	18000	202.5	71.6	6.0	280.1	5.0
Seed Drill	2	4.1.2	2.2	2	8000	90.0	31.8	2.7	124.5	2.2
	3	4.1.1	1.4	3	3000	33.8	11.9	1.0	46.7	0.8

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[2] See Section in Agro Business Consultants (1995) Farm Machinery Costings.

[3] Discounted at 1.125 percent per month.

[4] Insurance on self propelled vehicles (Tractors, Windrower, and Combine Harvestor) is charged at £ 12 / £ 1000 of the purchase price and £ 30 is charged for road licence fees. For other implements insurance is charged at £ 4 / £ 1000.

[5] For implements that are not self propelled, repairs and maintenance is calculated by summing the charges for the respective tractor and implement.

[6] The power ratings of tractors 1, 2 and 3 are 67-90 kW, 52-67 kW, and 37-52 kW and diesel fuel consumption rates 13.4, 10.2 and 7.7 l / hour, respectively.

Appendix 4.1 continued. Machinery Costs.

		Section	Work Rate (hectares / hour)	Minimum Tractor Required	a) Purchase Price (£)	b) Opportunity Cost of Capital (£ / month)	c) Sinking Fund (£ / month)	d) Road Fund License and Insurance (£ / month)	f) Total Monthly Payments (b + c + d) (£ / month)	Running Costs that vary with Machine Usage (£ / hour)
Conventional	1	4.2.3	2.6	1	14000	157.5	55.7	4.7	217.9	4.8
Combine	2	4.2.2	2.0	2	10500	118.1	41.8	3.5	163.4	3.6
Drill	3	4.2.1	1.2	3	4500	50.6	17.9	1.5	70.0	1.5
Fertilizer	1	5.1.3	n.a.	1	10000	112.5	39.8	3.3	155.6	3.5
Broadcaster[7]	2	5.1.2	n.a.	2	5000	56.3	19.9	1.7	77.9	1.8
	3	5.1.1	n.a.	3	1250	14.1	5.0	0.4	19.5	0.4
Conventional	1	6.1.3	6.5	1	12000	135.0	47.7	4.0	186.7	4.2
Sprayer	2	6.1.2	4.5	2	6000	67.5	23.9	2.0	93.4	2.1
	3	6.1.1	2.2	3	1250	14.1	5.0	0.4	19.5	0.4
Trailer	1	12.5.2	n.a.	3	4000	45.0	15.9	1.3	62.2	0.5
Mower	1	9.3.3	2.6	1	14500	163.1	57.7	4.8	225.6	5.7
	2	9.3.2	1.6	2	8000	90.0	31.8	2.7	124.5	3.15
	3	9.3.1	1.8	3	2000	22.5	8.0	0.7	31.2	0.8
Rake /	1	9.7.3	4.1	1	9000	101.3	35.8	3.0	140.1	3.4
Tedder /	2	9.7.2	3.2	2	4500	50.6	17.9	1.5	70.0	1.7
Turner	3	9.7.1	1.6	3	2000	22.5	8.0	0.7	31.2	0.8
Windrower[8]	1	7.2.1	1.9	n.a.	33000	371.3	131.3	32.8	535.4	2.4

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[7] Work rates are defined in tonnes of fertiliser / hour. The work rates are 0.4, 03. And 0.2 tonnes of fertiliser / hour respectively.

[8] The diesel fuel consumption rate is 13.6 l / hour.

Appendix 4.1 continued. Machinery Costs.

		Section	Work Rate (hectares / hour)	Minimum Tractor Required	a) Purchase Price (£)	b) Opportunity Cost of Capital (£ / month)	c) Sinking Fund (£ / month)	d) Road Fund License and Insurance (£ / month)	f) Total Monthly Payments (b + c + d) (£ / month)	Running Costs that vary with Machine Usage (£ / hour)
Conventional	1	8.1.2	1.2	2	12000	135.0	47.7	4.0	186.7	2.4
Hay Baler	2	8.1.1	0.9	3	6500	73.1	25.9	2.2	101.2	1.3
Forage	1	9.1.4	0.9	1	15000	168.8	59.7	5.0	233.5	5.7
Harvester	2	9.1.3	0.5	2	10500	118.1	41.8	3.5	163.4	4.0
	3	9.1.2	0.2	3	6000	67.5	23.9	2.0	93.4	2.3
Forage	1	9.5.2	0.7	2	18500	208.1	73.6	6.2	287.9	6.5
Wagon	2	9.5.1	0.5	3	12000	135.0	47.7	4.0	186.7	4.6
Potato	1	3.11.3	0.9	1	6000	67.5	23.9	2.0	93.4	0.9
Ridger	2	3.11.2	0.6	2	2500	28.1	9.9	0.8	38.8	0.4
Potato	1	4.8.3	1.4	1	15000	168.8	59.7	5.0	233.5	4.5
Planter	2	4.8.2	0.9	2	6500	73.1	25.9	2.2	101.2	2.0
	3	4.8.1	0.7	3	3000	33.8	11.9	1.0	46.7	0.9
Potato	1	7.8.3	0.4	1	37000	416.2	147.2	12.3	575.7	14.0
Harvester	2	7.8.2	0.3	2	26000	292.5	103.4	8.7	404.6	9.9
	3	7.8.1	0.2	3	15000	168.8	59.7	5	233.5	5.7
Power	1	3.7.3	1.9	1	10500	118.1	41.8	6.0	165.9	3.6
Harrows	2	3.7.2	1.4	2	6500	73.1	25.9	4.7	103.7	2.2
	3	3.7.1	1.0	3	3000	33.8	11.9	3.5	49.2	1.0
Combine	1	7.1.3	n.a.	n.a.	80000	900.0	318.2	75.8	1294.0	13.3
Harvester[9]	2	7.1.2	n.a.	n.a.	65000	731.3	258.5	62.1	1051.9	10.8
	3	7.1.1	n.a.	n.a.	45000	506.3	179.0	43.8	729.1	7.5

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[9] The work rate of the combine harvester is specified in tonnes matter other than grain / hour. The work rates of the harvesters are 7.2, 6.0 and 4.2 tonnes MOG / hour and the rates of diesel fuel consumption are 29.8, 17.8 and 13.2 l / hour. In addition 2 trailers and associated tractors are required per hour that the combine harvester is working.

Appendix 4.1 continued. Machinery Costs.

		Section	Work Rate (hectares / hour)	Minimum Tractor Required	a) Purchase Price (£)	b) Opportunity Cost of Capital (£ / month)	c) Sinking Fund (£ / month)	d) Road Fund License and Insurance (£ / month)	f) Total Monthly Payments (b + c + d) (£ / month)	Running Costs that vary with Machine Usage (£ / hour)
Farm Yard	1	5.4.3	n.a.	1	11000	123.8	43.8	3.7	171.3	3.7
Manure	2	5.4.2	n.a.	2	6500	73.1	25.9	2.2	101.2	2.3
Spreader[10]	3	5.4.1	n.a.	3	2250	25.3	8.9	0.8	35.0	0.8
Stone Clod Separator	1	3.12.1	0.8	2	12500	140.6	49.7	4.2	194.5	7.5
Stone / Clod Windrower	1	3.12.2	0.7	1	14500	163.1	57.7	4.8	225.6	8.7
Irrigator	1	12.1.1	1.0	3	11500	129.4	45.7	3.8	178.9	1.3

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[10] Work rates are defined in tonnes of manure / hour. The work rates are 15, 10 and 5 tonnes of manure / hour respectively.

Appendix 4.2 Buildings[11].

	Units	a) Purchase Price (£ / unit)	b) Opportunity Cost of Capital (£ / month)[12]	c) Monthly Sinking Fund[2]	d) Repairs and Maintenance[13]	e) Insurance	f) Total Monthly Payments (b+c+d+e)
Hay and Straw Barn[14]	m^3	12.1	0.14	0.00	0.01	0.00	0.15
Grain Storage[15]	m^3	57.0	0.64	0.01	0.06	0.02	0.73
Concentrate Storage[16]	m^3	14.2	0.16	0.00	0.01	0.00	0.18
Silage Pit[17]	tonnes	41.0	0.46	0.01	0.04	0.01	0.52
Potato Store[18]	tonnes	101.0	1.14	0.02	0.10	0.03	1.29
Animal Housing[19]	m^2	495.0	5.57	0.10	0.50	0.17	6.33
Dairy Parlor[20]	cow	2000.0	22.50	0.41	2.00	0.67	25.57

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[11] Source: SAC (1994). It is assumed that buildings have a 30 year life and zero scrap value after this time.

[12] Discounted at 1.125 percent per month.

[13] Assume 0.1 percent per month of purchase price

[14] Enclosed storage shed with steel sheeted walls. $200m^2 * 4.8m$ to eaves. It is assumed that hay requires $6m^3$ $tonne^{-1}$ and straw $12m^3$ $tonne^{-1}$ of storage space.

[15] On floor grain storage. $200m^2 * 3m$ of grain. It is assumed that rape requires $1.95m^3$ $tonne^{-1}$, barley $1.45m^3$ $tonne^{-1}$, and wheat $1.35m^3$ $tonne^{-1}$, respectively.

[16] Enclosed storage shed with steel sheeted walls and concrete floor. $200m^2 * 4.8m$ to eaves. It was assumed that $1.8m^2$ of space is required to store 1 tonne of concentrates.

[17] Silage clamp with concrete floor, effluent tank, and timber walls.

[18] Store potatoes to depth of 3.5m, includes ventilation system.

[19] Bedded cattle court with feeding passage. It is assumed that cattle require $4.2m^2$ of court space per head and sheep and lambs require $1.05m^2$ of space per head.

[20] Includes cubicles, parlour, equipment and covered collecting area.

Appendix 4.3. Storage of Feed Stuffs and Animal Housing.

	Type of Building	Storage Requirement
Hay	Hay and Straw Barn	167 kg / m^3
Straw	Hay and Straw Barn	83 kg / m^3
Barley	Grain Store	690 kg / m^3
Rape	Grain Store	512 kg / m^3
Wheat	Grain Store	740 kg / m^3
Maize Grain	Concentrate Store	550 kg / m^3
Wheat Bran	Concentrate Store	550 kg / m^3
Soya Bean Meal	Concentrate Store	550 kg / m^3
Linseed Meal	Concentrate Store	550 kg / m^3
Fish Meal	Concentrate Store	550 kg / m^3
Beef Cattle	Animal Housing	4.2 m^2 / animal
Dairy Cows	Animal Housing	5.6 m^2 / animal
Sheep	Animal Housing	1.0 m^2 / animal

Appendix 5. Crop Management and Machinery Operations.

Crop	Machinery Operation	Planting Date 1	Planting Date 2	Planting Date 3
1: Grass	Permit application of farm yard manure	February: 30 tonnes	(as for planting date 1, except permission given in March)	(as for planting date 1, except permission given in April)
	Permit broadcasting of fertiliser	April- July: 125 kg in each month	(as for planting date 1)	(as for planting date 1)
	Permit hay making	Mow, Ted * 2, Windrow, Bale	(as for planting date 1)	(as for planting date 1)
	Permit silage making	Forage Harvestor, Forage Wagon*2	(as for planting date 1)	(as for planting date 1)
2: Grass / Clover	(Operations as for Grass)			
3: Swedes	Apply farm yard manure	May: 30 tonnes	n/a	n/a
	Broadcast fertiliser	May: 250 kg	n/a	n/a
	Culivation	May: Plough, Power Harrow, Harrow, Drill	n/a	n/a
	Spray	May * 1	n/a	n/a

Appendix 5 continued. Crop Management and Machinery Operations.

Crop	Machinery Operation	Planting Date 1	Planting Date 2	Planting Date 3
4: Potatoes	Apply farm yard manure	November: 30 tonnes	(as for planting date 1, except permission given in December)	(as for planting date 1, except permission given in January)
	Require drilling or broadcasting of fertiliser	March: 1000 kg	(as for planting date 1, except permission given in April)	(as for planting date 1, except permission given in May)
	Cultivation	November: Plough; March: Rotovate, Power Harrow, Potato Ridge, Stone / Clod Separator, Stone / Clod Windrower, Harrow, Potato Planter	(as for planting date 1, except operations delayed by a month)	(as for planting date 1, except operations delayed by 2 months)
	Spray	May *1 June * 2 July * 3 August * 2	(as for planting date 1)	(as for planting date 1)
	Irrigation	July * 3	(as for planting date 1)	(as for planting date 1)
	Harvesting	September: Desiccate, Potato Harvester	(as for planting date 1)	(as for planting date 1)
	Residue Disposal	Incorporate (timing as per cultivation of incoming crop)	(as for planting date 1)	(as for planting date 1)

Appendix 5 continued. Crop Management and Machinery Operations.

Crop	Machinery Operation	Planting Date 1	Planting Date 2	Planting Date 3
5: Spring Feed Barley	Permit application of farm yard manure	December: 30 tonnes	(as for planting date 1, except permission given in January)	(as for planting date 1, except permission given in February)
	Permit drilling or broadcasting of fertiliser	March: 500 kg	(as for planting date 1, except permission given in April)	(as for planting date 1, except permission given in May)
	Cultivation	December: Plough March: Power Harrow, Harrow, Roll, Drill	(as for planting date 1, except operations delayed by a month)	(as for planting date 1, except operations delayed by 2 months)
	Spray	May * 1 June * 1	(as for planting date 1)	(as for planting date 1)
	Harvesting	September: Combine Harvestor, Tractor / Trailer * 2, Crop drier	(as for planting date 1)	(as for planting date 1)
	Residue Disposal	Incorporate (timing as per cultivation of incoming crop) or bale (September)	(as for planting date 1)	(as for planting date 1)
6: Spring Feed Barley (undersown)	(Operations as for Spring Feed Barley, except residues must be baled in September)			

Appendix 5 continued. Crop Management and Machinery Operations.

Crop	Machinery Operation	Planting Date 1	Planting Date 2	Planting Date 3
7: Vining Peas	Require application of farm yard manure	December: 30 tonnes	(as for planting date 1, except permission given in January)	(as for planting date 1, except permission given in February)
	Require drilling or broadcasting of fertiliser	March: 100 kg	(as for planting date 1, except permission given in April)	(as for planting date 1, except permission given in May)
	Cultivation	December: Plough, March: Power Harrow, Harrow, Roll, Drill	(as for planting date 1, except operations delayed by a month)	(as for planting date 1, except operations delayed by 2 months)
	Spray	May * 1 June * 2	(as for planting date 1)	(as for planting date 1)
	Harvesting	September: Company that contracts farm to grow crop, supplies machinery for harvesting		
	Residue Disposal	Incorporated (timing as per cultivation of incoming crop) or Grazed (September)	(as for planting date 1)	(as for planting date 1)

Appendix 5 continued. Crop Management and Machinery Operations.

Crop	Machinery Operation	Planting Date 1	Planting Date 2	Planting Date 3
8: Winter Oilseed Rape	Permit application of farm yard manure	July: 30 tonnes	(as for planting date 1, except permission given in August)	(as for planting date 1, except permission given in September)
	Permit drilling or broadcasting of fertiliser	July: 300 kg	(as for planting date 1, except permission given in August)	(as for planting date 1, except permission given in September)
	Permit broadcasting of fertiliser	April: 600 kg	(as for planting date 1)	(as for planting date 1)
	Cultivation	July: Plough, Power Harrow, Harrow, Roll, Drill	(as for planting date 1, except operations delayed by a month)	(as for planting date 1, except operations delayed by 2 months)
	Spray	October * 1 November *1 May * 1	(as for planting date 1)	(as for planting date 1)
	Harvesting	August: Dessicate, Windrow, Combine Harvestor Tractor / Trailer Unit * 2	(as for planting date 1)	(as for planting date 1)
	Residue Disposal	Incorporated (timing as per cultivation of incoming crop)	(as for planting date 1)	(as for planting date 1)

Appendix 5 continued. Crop Management and Machinery Operations.

Crop	Machinery Operation	Planting Date 1	Planting Date 2	Planting Date 3
9: Winter Feed Barley	Permit application of farm yard manure	September: 30 tonnes	(as for planting date 1, except permission given in October)	(as for planting date 1, except permission given in November)
	Permit drilling or broadcasting of fertiliser	September: 250 kg	(as for planting date 1, except permission given in October)	(as for planting date 1, except permission given in November)
	Permit broadcasting of fertiliser	April: 400 kg	(as for planting date 1)	(as for planting date 1)
	Cultivation	September: Plough, Power Harrow, Harrow, Drill	(as for planting date 1, except operations delayed by a month)	(as for planting date 1, except operations delayed by 2 months)
	Spray	Month of planting* 1, November * 1, March * 1, May * 1, June * 1	(as for planting date 1)	(as for planting date 1)
	Harvesting	August: Combine Harvestor, Tractor / Trailer Unit * 2 Crop Drier	(as for planting date 1)	(as for planting date 1)
	Residue Disposal	Incorporate (timing as per cultivation of incoming crop) or bale (August)	(as for planting date 1)	(as for planting date 1)

Appendix 5 continued. Crop Management and Machinery Operations.

Crop	Machinery Operation	Planting Date 1	Planting Date 2	Planting Date 3
10: Winter Malting Barley	(Operations as for Winter Feed Barley)			
11: Winter Feed Wheat	Permit application of farm yard manure	October: 30 tonnes	(as for planting date 1, except permission given in November)	(as for planting date 1, except permission given in December)
	Permit drilling or broadcasting of fertiliser	October: 450 kg	(as for planting date 1, except permission given in November)	(as for planting date 1, except permission given in December)
	Permit broadcasting of fertiliser	April: 250 kg	(as for planting date 1)	(as for planting date 1)
	Cultivation	October: Plough, Power Harrow, Harrow, Roll, Drill	(as for planting date 1, except operations delayed by a month)	(as for planting date 1, except operations delayed by 2 months)
	Spray	Month of planting * 1, March * 1, April * 1, May * 1, June * 2	(as for planting date 1)	(as for planting date 1)

Appendix 5 continued. Crop Management and Machinery Operations.

Crop	Machinery Operation	Planting Date 1	Planting Date 2	Planting Date 3
11: Winter Feed Wheat continued.	Harvesting	September: Combine Harvestor Tractor / Trailer Unit * 2 Crop Drier	(as for planting date 1)	(as for planting date 1)
	Residue Disposal	Incorporate (timing as per cultivation of incoming crop) or bale (September)	(as for planting date 1)	(as for planting date 1)
12: Winter Milling Wheat	(Operations as for Winter Feed Wheat)			

Appendix 6. Potential Production of Pasture and Crops and Significance of Differences with Climate ‘0’.

Potential Growth of Grass / Clover Leaf (kg / hectare)

Climate	‘0’				‘1’				‘2’			
Soil	‘1’	‘2’	‘3’	‘4’	‘1’	‘2’	‘3’	‘4’	‘1’	‘2’	‘3’	‘4’
Kinloss	3281	3467	3624	3839	3210 n.s.	3518 n.s.	3582 n.s.	3740 n.s.	3185 n.s.	3487 n.s.	3585 n.s.	3680 n.s.
Mylnefield	3461	3757	3725	3913	3808 **	4031 n.s.	4387 **	4371 **	3712 n.s.	3865 n.s.	3802 n.s.	4291 n.s.
Paisley	3593	3706	3727	4006	3694 n.s.	3920 n.s.	3987 n.s.	4106 n.s.	3951 n.s.	4046 n.s.	4083 n.s.	4381 n.s.
Wick	3321	3344	3536	3614	3420 n.s.	3525 n.s.	3612 n.s.	3761 n.s.	3171 n.s.	3224 n.s.	3344 n.s.	3507 n.s.

Potential Growth of Grass Leaf (kg / hectare)

Climate	‘0’				‘1’				‘2’			
Soil	‘1’	‘2’	‘3’	‘4’	‘1’	‘2’	‘3’	‘4’	‘1’	‘2’	‘3’	‘4’
Kinloss	4551	4661	4943	5142	4487 n.s.	4606 n.s.	4926 n.s.	4943 n.s.	4557 n.s.	4617 n.s.	4901 n.s.	5024 n.s.
Mylnefield	4517	4990	5003	5220	5032 **	5160 n.s.	5757 **	5588 n.s.	4812 n.s.	5052 n.s.	5432 n.s.	5632 n.s.
Paisley	4831	4978	5265	5359	4997 n.s.	5227 n.s.	5472 n.s.	5522 n.s.	5309 n.s.	5505 **	5674 n.s.	5882 n.s.
Wick	4372	4602	4860	5116	4563 n.s.	4646 n.s.	4622 n.s.	5017 n.s.	4059 n.s.	4237 n.s.	4410 n.s.	4778 n.s.

** - significance at the 5 % level, n.s. - not significant

Appendix 6 continued. Potential Production of Pasture and Crops and Significance of Differences with Climate ‘0’.

Potential Production of Potatoes (kg / hectare)

Region		Kinloss			Mylnefield			Paisley			Wick		
Climate		‘0’	‘1’	‘2’	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’
Sowing Date	1	15618	21021 **	22669 **	19334	22022 n.s.	19264 n.s.	20237	24388 **	24208 **	11808	22149 **	20920 **
	2	14767	19050 **	19967 **	14008	18126 **	14248 n.s.	18850	21482 n.s.	20291 n.s.	10399	19118 **	16910 **
	3	10104	16546 **	13817 **	9982	14001 **	11383 n.s.	12036	15795 **	16059 **	8505	14714 **	11722 **

Potential Production of Winter Milling Wheat (kg / hectare).

Region		Kinloss			Mylnefield			Paisley			Wick		
Climate		‘0’	‘1’	‘2’	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’
Sowing Date	1	5081	6200 **	7345 **	7790	7280 n.s.	8009 n.s.	7997	6313 **	6064 **	4721	7410 **	7305 **
	2	5015	5549 **	6304 **	6765	6280 n.s.	6793 n.s.	7344	5571 **	5589 **	5106	6399 **	6908 **
	3	5235	5350 n.s.	5660 n.s.	6520	5225 **	6586 n.s.	6224	4892 **	4524 **	5799	5672 n.s.	6889 **

** - significance at the 5 % level, n.s. - not significant

Appendix 6 continued. Potential Production of Pasture and Crops and Significance of Differences with Climate '0'.

Potential Production of Winter Feed Wheat (kg / hectare).

Kinloss													
Climate		'0'				'1'				'2'			
Soil		'1'	'2'	'3'	'4'	'1'	'2'	'3'	'4'	'1'	'2'	'3'	'4'
Sowing Date	1	4263	4476	4658	4827	5100 **	5487 **	5679 **	5878 **	6031 **	6446 **	6681 **	6933 **
	2	4201	4470	4700	4813	4355 n.s.	4899 n.s.	5208 **	5314 **	4848 **	5439 **	5755 **	6012 **
	3	4260	4582	4980	5014	4222 n.s.	4819 n.s.	5015 n.s.	5160 n.s.	4545 n.s.	5042 **	5314 n.s.	5449 n.s.

Mylnefield													
Climate		'0'				'1'				'2'			
Soil		'1'	'2'	'3'	'4'	'1'	'2'	'3'	'4'	'1'	'2'	'3'	'4'
Sowing Date	1	6359	6987	7312	7332	5824 n.s.	6287 **	6562 **	6887 n.s.	6478 n.s.	7258 n.s.	7494 n.s.	7525 n.s.
	2	5592	5932	6375	6387	4969 **	5540 n.s.	5864 n.s.	5965 n.s.	5761 n.s.	5984 n.s.	6367 n.s.	6489 n.s.
	3	5447	5939	6099	6183	4141 **	4768 **	4883 **	5045 **	5349 n.s.	6002 n.s.	6102 n.s.	6286 n.s.

** - significance at the 5 % level, n.s. - not significant

Appendix 6 continued. Potential Production of Pasture and Crops and Significance of Differences with Climate ‘0’.

Potential Production of Winter Feed Wheat (kg / hectare).

Paisley													
Climate		‘0’				‘1’				‘2’			
Soil		‘1’	‘2’	‘3’	‘4’	‘1’	‘2’	‘3’	‘4’	‘1’	‘2’	‘3’	‘4’
Sowing Date	1	6041	6909	7204	7456	5109 **	5512 **	5812 **	6035 **	5054 **	5371 **	5603 **	5798 **
	2	5929	6244	6634	6920	4486 **	4831 **	5175 **	5387 **	4510 **	4916 **	5243 **	5408 **
	3	5133	5538	5713	5903	3918 **	4357 **	4659 **	4776 **	3906 **	4139 **	4344 **	4418 **

Wick													
Climate		‘0’				‘1’				‘2’			
Soil		‘1’	‘2’	‘3’	‘4’	‘1’	‘2’	‘3’	‘4’	‘1’	‘2’	‘3’	‘4’
Sowing Date	1	3883	4030	4380	4505	5975 **	6541 **	6805 **	6941 **	5951 **	6477 **	6831 **	6873 **
	2	3966	4537	4647	4833	4983 **	5689 **	5835 **	6061 **	5813 **	5885 **	6389 **	6573 **
	3	4850	5074	5322	5466	4667 n.s.	4935 n.s.	5293 n.s.	5416 n.s.	5460 **	6018 **	6331 **	6583 **

** - significance at the 5 % level, n.s. - not significant

Appendix 6 continued. Potential Production of Pasture and Crops and Significance of Differences with Climate '0'.

Potential Production of Spring Feed Barley (kg / hectare)

Kinloss													
Climate		'0'				'1'				'2'			
Soil		'1'	'2'	'3'	'4'	'1'	'2'	'3'	'4'	'1'	'2'	'3'	'4'
Sowing Date	1	4768	4768	4768	4768	6647	6647	6647	6647 **	7042	7042	7042	7042 **
	2	4200	4200	4200	4200	6236	6236	6236	6236 **	6772	6772	6772	6772 **
	3	3491	3491	3491	3491	5893	5893	5893	5893 **	5320	5320	5320	5320 **

Mylnefield													
Climate		'0'				'1'				'2'			
Soil		'1'	'2'	'3'	'4'	'1'	'2'	'3'	'4'	'1'	'2'	'3'	'4'
Sowing Date	1	6037	6037	6037	6037	5941	5941	5941	5941 n.s.	8075	8075	8075	8075 **
	2	5066	5066	5066	5066	5058	5058	5058	5058 n.s.	7442	7442	7442	7442 **
	3	4081	4081	4081	4081	4315	4315	4315	4315 n.s.	7061	7061	7061	7061 **

** - significance at the 5 % level, n.s. - not significant

Appendix 6 continued. Potential Production of Pasture and Crops and Significance of Differences with Climate ‘0’.

Potential Production of Spring Feed Barley (kg / hectare)

Paisley													
Climate		‘0’				‘1’				‘2’			
Soil		‘1’	‘2’	‘3’	‘4’	‘1’	‘2’	‘3’	‘4’	‘1’	‘2’	‘3’	‘4’
Sowing Date	1	7053	7053	7053	7053	5979	5979	5979	5979 **	6190	6190	6190	6190 **
	2	6555	6555	6555	6555	6035	6035	6035	6035 n.s.	6426	6426	6426	6426 n.s.
	3	5273	5273	5273	5273	5325	5325	5325	5325 n.s.	5855	5855	5855	5855 **

Wick													
Climate		‘0’				‘1’				‘2’			
Soil		‘1’	‘2’	‘3’	‘4’	‘1’	‘2’	‘3’	‘4’	‘1’	‘2’	‘3’	‘4’
Sowing Date	1	4394	4394	4394	4394	6268	6268	6268	6268 **	6813	6813	6813	6813 **
	2	3822	3822	3822	3822	5893	5893	5893	5893 **	6280	6280	6280	6280 **
	3	3088	3088	3088	3088	5391	5391	5391	5391 **	5032	5032	5032	5032 **

** - significance at the 5 % level, n.s. - not significant

Appendix 6 continued. Potential Production of Pasture and Crops and Significance of Differences with Climate ‘0’.

Potential Production of Winter Feed Barley (kg / hectare)

Kinloss													
Climate		‘0’				‘1’				‘2’			
Soil		‘1’	‘2’	‘3’	‘4’	‘1’	‘2’	‘3’	‘4’	‘1’	‘2’	‘3’	‘4’
Sowing Date	1	5475	5956	6275	6756	1532	1996	2305	2772 **	735	1219	1543	2028 **
	2	6320	6797	7116	7593	3952	4435	4758	5241 **	3102	3584	3906	4387 **
	3	6693	7156	7465	7929	5948	6432	6755	7238 n.s.	4933	5417	5737	6221 **

Mylnefield													
Climate		‘0’				‘1’				‘2’			
Soil		‘1’	‘2’	‘3’	‘4’	‘1’	‘2’	‘3’	‘4’	‘1’	‘2’	‘3’	‘4’
Sowing Date	1	7606	8081	8400	8880	2394	2851	3154	3612 **	1533	2020	2343	2829 **
	2	8621	9103	9425	9908	4866	5351	5673	6158 **	4079	4559	4880	5366 **
	3	8524	8990	9301	9767	6310	6794	7117	7602 **	6708	7191	7514	7997 **

** - significance at the 5 % level, n.s. - not significant

Appendix 6 continued. Potential Production of Pasture and Crops and Significance of Differences with Climate ‘0’.

Potential Production of Winter Feed Barley (kg / hectare)

Paisley													
Climate		‘0’				‘1’				‘2’			
Soil		‘1’	‘2’	‘3’	‘4’	‘1’	‘2’	‘3’	‘4’	‘1’	‘2’	‘3’	‘4’
Sowing Date	1	6854	7338	7656	8139	1581	2060	2384	2870 **	624	1015	1337	1824 **
	2	8736	9219	9542	10023	3232	3717	4038	4523 **	2087	2498	2800	3285 **
	3	9732	10219	10541	11025	4759	5243	5565	6050 **	4400	4875	5191	5665 **

Wick													
Climate		‘0’				‘1’				‘2’			
Soil		‘1’	‘2’	‘3’	‘4’	‘1’	‘2’	‘3’	‘4’	‘1’	‘2’	‘3’	‘4’
Sowing Date	1	5261	5741	6061	6541	1660	2075	2353	2771 **	1026	1509	1833	2319 **
	2	5945	6421	6739	7216	3393	3873	4196	4677 **	2903	3386	3707	4188 **
	3	6234	6718	7040	7525	5244	5727	6051	6537 **	6673	7156	7477	7964 n.s.

** - significance at the 5 % level, n.s. - not significant

Appendix 6 continued. Potential Production of Pasture and Crops and Significance of Differences with Climate '0'.

Potential Production of Vining Peas (kg / hectare)

Region		Kinloss			Mylnefield			Paisley			Wick		
Climate		'0'	'1'	'2'	'0'	'1'	'2'	'0'	'1'	'2'	'0'	'1'	'2'
Sowing Date	1	5860	7258 **	7588 **	7074	6543 n.s.	8601 **	8086	6655 **	6823 **	5626	7235 **	7411 **
	2	5402	7283 **	7469 **	6197	6197 n.s.	8433 **	7612	6744 **	7146 n.s.	5032	7034 **	7356 **
	3	4501	6801 **	6246 **	5081	5337 n.s.	7878 **	6157	6310 n.s.	6809 **	4108	6294 **	5925 **

Potential Production of Winter Oilseed Rape (kg / hectare)

Region		Kinloss			Mylnefield			Paisley			Wick		
Climate		'0'	'1'	'2'	'0'	'1'	'2'	'0'	'1'	'2'	'0'	'1'	'2'
Sowing Date	1	3092	2039 **	1394 **	4094	2049 **	1878 **	3172	1954 **	2014 **	3274	1763 **	1405 **
	2	3421	1912 **	1353 **	4118	2306 **	1568 **	3798	1802 **	1352 **	2820	1970 **	1463 **
	3	3153	2996 n.s.	2385 **	3684	3123 **	2858 **	3537	2571 **	2187 **	2738	2904 n.s.	2852 n.s.

** - significance at the 5 % level, n.s. - not significant

Appendix 7. Potential Growth of Grass / Clover Leaf (kg / hectare) (see a2 in equation 5.3)

Kinloss												
Climate	‘0’				‘1’				‘2’			
Soil	‘1’	‘2’	‘3’	‘4’	‘1’	‘2’	‘3’	‘4’	‘1’	‘2’	‘3’	‘4’
January	0	0	0	0	71	85	89	84	71	60	67	69
February	4	4	4	4	131	130	144	147	102	107	93	116
March	70	85	84	82	160	163	183	185	149	183	186	167
April	169	179	183	187	268	290	318	336	270	288	330	318
May	418	402	436	396	426	460	501	539	433	481	495	527
June	542	616	696	713	590	648	682	651	582	627	690	671
July	664	675	648	810	571	658	638	701	600	688	644	668
August	446	477	515	514	430	481	421	505	412	415	453	467
September	310	309	336	368	246	280	266	281	267	296	287	299
October	239	267	261	261	175	173	186	167	163	186	185	203
November	187	199	191	215	60	67	67	64	60	66	70	74
December	233	256	270	288	83	82	89	81	77	90	86	100

Mylnefield												
Climate	‘0’				‘1’				‘2’			
Soil	‘1’	‘2’	‘3’	‘4’	‘1’	‘2’	‘3’	‘4’	‘1’	‘2’	‘3’	‘4’
January	16	15	16	18	72	73	78	83	76	91	90	90
February	31	30	32	33	119	138	134	130	119	109	109	119
March	126	140	126	143	202	197	206	234	217	203	202	223
April	248	306	313	287	356	362	366	374	359	346	339	375
May	462	532	506	526	537	644	664	653	527	497	575	643
June	766	808	774	786	812	748	867	847	759	750	748	882
July	631	708	731	796	651	723	824	816	663	763	711	824
August	432	419	412	481	469	488	548	534	431	497	428	498
September	295	306	294	320	293	320	352	364	281	286	291	323
October	175	175	201	188	146	173	183	171	141	176	157	160
November	122	146	135	152	68	69	71	74	59	63	61	74
December	157	172	186	184	83	97	94	93	80	84	91	79

Appendix 7 continued. Potential Growth of Grass / Clover Leaf (kg / hectare) (see a2 in equation 5.3)

Paisley												
Climate	'0'				'1'				'2'			
Soil	'1'	'2'	'3'	'4'	'1'	'2'	'3'	'4'	'1'	'2'	'3'	'4'
January	13	15	15	15	92	84	88	104	84	85	92	99
February	15	18	20	20	143	132	144	142	108	113	131	127
March	105	115	103	114	201	236	240	234	202	228	230	211
April	232	241	247	279	316	332	346	341	288	356	313	378
May	430	474	443	531	443	518	504	565	526	557	502	617
June	718	734	700	825	751	798	798	826	813	760	881	899
July	712	794	820	738	728	721	708	721	727	657	694	745
August	493	452	456	532	386	415	425	479	453	501	487	498
September	341	291	364	373	270	314	349	318	322	346	319	363
October	210	214	224	218	190	199	201	187	188	196	180	179
November	145	153	147	156	73	68	75	86	93	106	103	117
December	179	206	189	206	102	103	108	103	146	143	150	147

Wick												
Climate	'0'				'1'				'2'			
Soil	'1'	'2'	'3'	'4'	'1'	'2'	'3'	'4'	'1'	'2'	'3'	'4'
January	9	10	11	10	48	46	48	54	56	52	59	59
February	37	37	37	46	86	109	107	99	116	106	116	130
March	86	79	98	96	168	173	180	196	146	178	186	194
April	253	216	254	280	278	262	298	313	300	313	303	310
May	434	452	499	456	465	461	445	501	468	451	480	504
June	641	725	720	795	745	661	795	724	573	657	610	659
July	626	643	600	647	674	767	669	725	600	589	628	658
August	420	415	451	415	452	477	514	532	365	344	376	440
September	289	248	314	315	248	279	270	302	270	263	294	260
October	187	176	194	187	126	140	145	154	148	148	152	157
November	148	151	148	160	57	58	56	62	52	48	55	55
December	191	191	211	206	75	93	84	100	77	75	85	82

Appendix 7 continued. Potential Growth of Grass Leaf (kg / hectare) (see a2 in equation 5.3)

Kinloss												
Climate	'0'				'1'				'2'			
Soil	'1'	'2'	'3'	'4'	'1'	'2'	'3'	'4'	'1'	'2'	'3'	'4'
January	0	0	0	0	82	78	82	90	73	67	81	82
February	4	4	4	4	117	125	144	137	111	109	104	119
March	83	98	99	105	189	237	240	240	235	216	258	244
April	240	233	240	230	387	377	427	483	475	486	468	511
May	590	613	645	667	573	693	660	642	596	617	745	791
June	821	810	928	949	921	852	927	958	809	835	909	867
July	797	950	940	983	856	825	946	908	866	799	819	884
August	627	588	592	709	553	627	619	599	536	572	602	556
September	420	403	479	450	387	358	381	390	390	434	381	425
October	368	343	355	376	217	226	275	259	250	253	297	288
November	274	244	277	278	88	102	103	108	107	93	100	117
December	327	376	385	390	118	108	125	129	110	136	136	140

Mylnefield												
Climate	'0'					'1'			'2'			
Soil	'1'	'2'	'3'	'4'	'1'	'2'	'3'	'4'	'1'	'2'	'3'	'4'
January	17	17	20	21	77	69	82	75	74	77	96	97
February	35	39	36	41	136	119	138	136	111	112	118	115
March	161	162	176	182	252	282	295	293	239	241	300	287
April	393	398	428	453	451	535	488	526	428	459	513	570
May	651	680	670	746	733	754	877	808	776	735	851	835
June	889	1022	989	1071	959	982	1140	1067	880	1058	1070	1029
July	880	973	947	962	891	935	1020	1010	879	891	1032	1041
August	513	569	525	566	630	636	702	698	581	652	577	695
September	348	432	454	448	463	410	502	471	380	374	401	446
October	230	273	301	271	218	223	281	260	246	235	231	263
November	179	197	185	202	104	96	99	109	101	92	114	116
December	221	228	272	258	118	119	133	133	115	125	129	139

Appendix 7 continued. Potential Growth of Grass Leaf (kg / hectare) (see a2 in equation 5.3)

Paisley												
Climate	'0'				'1'				'2'			
Soil	'1'	'2'	'3'	'4'	'1'	'2'	'3'	'4'	'1'	'2'	'3'	'4'
January	13	14	16	17	93	88	91	96	86	84	103	110
February	17	19	19	22	128	148	170	159	126	122	114	118
March	109	134	122	137	263	286	313	295	258	258	318	329
April	337	344	412	407	376	443	461	500	494	461	490	551
May	619	619	700	645	736	685	736	747	780	735	709	863
June	910	1080	1065	1108	946	1099	1101	1159	963	1129	1074	1054
July	964	906	1038	1020	960	936	926	1008	881	999	1089	997
August	661	627	610	667	570	606	630	577	651	684	712	711
September	469	451	457	488	402	390	487	428	459	436	467	499
October	257	318	306	320	269	283	305	285	259	250	267	283
November	212	206	235	217	102	106	117	121	151	132	147	144
December	264	261	285	311	151	157	138	146	202	215	184	223

Wick												
Climate	'0'				'1'				'2'			
Soil	'1'	'2'	'3'	'4'	'1'	'2'	'3'	'4'	'1'	'2'	'3'	'4'
January	12	12	12	12	52	45	55	57	49	58	58	64
February	44	47	42	52	106	110	113	104	101	114	107	114
March	98	107	114	113	198	226	202	230	204	206	210	230
April	314	306	321	387	331	375	427	442	359	406	407	464
May	642	660	634	652	652	657	597	692	527	591	679	638
June	901	894	1026	1100	965	981	880	1005	728	906	774	957
July	716	863	924	898	967	906	953	966	828	757	913	923
August	560	586	576	602	566	552	595	704	526	461	495	553
September	401	406	406	448	343	392	369	365	384	335	367	403
October	252	263	293	310	176	185	213	207	186	215	201	224
November	196	199	219	234	81	86	89	102	67	69	79	86
December	237	260	295	307	127	132	130	143	99	120	121	124

Appendix 8. Sources of Trial Data.

Spring Feed Barley

Report	Year	Page(s)	Experiment Title
1	1967	pp 25	Spring Cereal Species and Manuring
1	1967	pp 28-30	Anhydrous Ammonia on Barley
1	1967	pp 47-49	Intensive Cereal Growing
1	1967	pp 55-57	Long Term Manuring
1	1968	pp 32-41	Nitrogen Level, Seed Rate, Barley Variety Trial
1	1968	pp 60	Intensive Cereal Growing
1	1968	pp 65-70	Long Term Manuring
1	1969	pp 27-31	Anhydrous Ammonia on Barley
1	1969	pp 44	Intensive Cereal Growing
1	1970	pp 25-26	Anhydrous Ammonia on Barley
1	1973	pp 42	Intensive Cereal Growing Trial
1	1974	pp 49	Intensive Cereal Growing Trial
1	1975	pp 27	Intensive Cereal Growing Trials
2	1976	pp 40	Intensive Cereal Growing Trials
2	1976	pp 46	Cultivation Methods for Continuous Cereals
2	1977	pp 43	Cultivation Methods for Continuous Cereals
2	1978	pp 38-41	Barley Seedbed Preparation
2	1978	pp 43	Cultivation Methods for Continuous Cereals
2	1978	pp 52	Maximising Yield in Barley
2	1979	pp 55	Spring Barley Growth Regulations
2	1980	pp 37	Cultivation Methods for Continuous Barley
2	1980	pp 50	Spring Barley Growth Regulators
2	1981	pp 28	Cultivation Methods for continuous Barley
2	1983	pp 37	Cultivation Methods for Continuous Barley
2	1984	pp 16-19	Spring Barley Systems
2	1985	pp 70	Spring Barley Systems
2	1986	pp 58	Spring Barley Systems
2	1986	pp 63	Late Liquid N Fertiliser
2	1986	pp 66	The Effects of Dicyandiamide
3	1987	pp 103	Spring Barley Systems
3	1988	pp 120	Spring Barley Systems
3	1989	pp 97	Spring Barley Systems

1: Report of County Experiments, East of Scotland College of Agriculture.
2: Report of Field Experiments and Surveys, East of Scotland College of Agriculture.
3: Report of Field Experiments and Surveys, Scottish Agricultural College.

Appendix 8 continued. Sources of Trial Data.

Winter Feed Barley

Report	Year	Page(s)	Experiment Title
2	1980	pp 32	Direct Drilling of Barley
2	1981	pp 62	Winter Barley Manuring
2	1981	pp 67	Primary Cultivations for Winter Barley
2	1983	pp 84	Winter Barley Manuring
2	1983	pp 97	Reduced Cultivations for Winter Barley
2	1983	pp 98	Direct Drilling of Winter Barley
2	1984	pp 39	Winter Barley Systems
2	1985	pp 14	Winter Barley Systems
2	1985	pp 18	Rate and Timing of Nitrogen Fertiliser Application
2	1986	pp 17	Winter Barley Systems
2	1986	pp 24	Nitrogen Rate and Timing
3	1987	pp 15	Winter Barley Systems
3	1987	pp 20	Nitrogen Rate and Timing for Winter Barley
3	1988	pp 18	Winter Barley Systems
3	1989	pp 19	Winter Barley Systems
3	1990	pp 11	Winter Barley Systems

Vining Peas.

Report	Year	Page(s)	Experiment Title
1	1973	pp 52	Dried Pea Variety Trial
2	1977	pp 69	Dried Pea Variety Trial
2	1980	pp 235	Dried Pea Variety Trial
2	1981	pp 129	Dried Pea Variety Trial
2	1983	pp 181	Dried Pea Variety Trial
2	1984	pp 181	Dried Pea Variety Trial
2	1985	pp 113	Pea Variety Trial
2	1986	pp 115	Pea Variety Trial
2	1986	pp 119	Pea Growth Regulator Trial
3	1987	pp 186	Pea Variety Trial
3	1987	pp 190	Pea Seed Rates Trial
3	1987	pp 192	Pea Fungicide Trial
3	1989	pp 199	Combining Peas Variety Trial
3	1989	pp 202	Combining Pea Seed Rates
3	1989	pp 204	Combining Pea Response to Weed Control
3	1989	pp 210	Pea Fungicide Trial
3	1990	pp 235	Pea Variety Trial
3	1990	pp 238	Seed Rate Trial
3	1990	pp 240	Fungicide Trial
3	1990	pp 242	Combining Trial

1: Report of County Experiments, East of Scotland College of Agriculture.
2: Report of Field Experiments and Surveys, East of Scotland College of Agriculture.
3: Report of Field Experiments and Surveys, Scottish Agricultural College.

Appendix 8 continued. Sources of Trial Data.

Winter Oilseed Rape.

Report	Year	Page(s)	Experiment Title
2	1985	pp 111	Population Trial
2	1986	pp 108	Variety Trial
2	1986	pp 110	Row Width and Seed Rate Trial
2	1986	pp 113	Autumn Nitrogen and Early Fungicides Trial
3	1987	pp 157	Variety Trial
3	1987	pp 162	Nitrogen Trial
3	1987	pp 165	Fungicide Trial
3	1987	pp 169	Fungicide Trial
3	1987	pp 173	Weed Control Trial
3	1987	pp 179	Graminicide Trial
3	1988	pp 164	Variety Trial
3	1988	pp 170	Nitrogen Trial
3	1988	pp 172	Micronutrient Trial
3	1988	pp 175	Weed Control Trial
3	1988	pp 184	Fungicide Trial
3	1988	pp 188	Growth Regulator Trials
3	1989	pp 154	Variety Trial
3	1989	pp 159	Management Systems Trials
3	1989	pp 164	Herbicide Trial
3	1989	pp 179,183	Fungicide Trial
3	1989	pp 188	Micronutrient Trials
3	1990	pp 158	Fungicide Trial
3	1990	pp 166	Seed rate * Autumn N * Spring N * Growth Regulator
3	1990	pp 171	Herbicide Trial
3	1990	pp 188	Herbicide Trial

1: Report of County Experiments, East of Scotland College of Agriculture.
2: Report of Field Experiments and Surveys, East of Scotland College of Agriculture.
3: Report of Field Experiments and Surveys, Scottish Agricultural College.

Appendix 8 continued. Sources of Trial Data.

Winter Wheat

Report	Year	Page(s)	Experiment Title
1	1967	pp 34	Cloremequat on Winter Wheat
1	1967	pp 44, 48	Intensive Cereal Growing
1	1968	pp 47	Anhydrous Ammonia on Winter Wheat
1	1968	pp 53, 56	Intensive Cereal Growing
1	1969	pp 35, 36	Anhydrous Ammonia on Winter Wheat
1	1969	pp 47, 50	Intensive Cereal Growing
1	1970	pp 27-31	Anhydrous Ammonia on Winter Wheat
1	1970	pp 43, 47, 55	Intensive Cereal Growing
1	1970	pp 58	Long Term Manuring
1	1971	pp 27	Wheat Varieties, N Level, Cyclocel
1	1971	pp 36, 39	Intensive Cereal Growing Trials
1	1974	pp 49-50	Intensive Cereal Growing Trials
1	1975	pp 27	Intensive Cereal Growing Trials
2	1976	pp 40-43	Intensive Cereal Growing Trials
2	1983	pp 125, 127	Winter Wheat Varieties
2	1984	pp 76	Winter Wheat Varieties
2	1984	pp 80	Winter Wheat Systems
2	1985	pp 43	Winter Wheat Systems
2	1985	pp 49	The Effect of Dicyandiamide on Winter Wheat.
2	1985	pp 51	Effect of Late Application of Nitrogen as Urea Solutions on the Protein Content of Wheat for Bread Making
2	1986	pp 35	Winter Wheat Systems
2	1986	pp 39	Winter Wheat Growth Regulator Trials
2	1986	pp 41	Winter Wheat Protein Quality
2	1986	pp 42, 44	The Effect of Dicyandiamide on the Yield of Winter Wheat.
3	1987	pp 59	Winter Wheat Systems
3	1987	pp 65	The Effect of Dicyandiamide on the Yield of Winter Wheat.
3	1989	pp 48	Winter Wheat Systems
3	1989	pp 52	Nitrogen Timing in Winter Wheat
3	1990	pp 47	Winter Wheat Systems
3	1990	pp 100	Nitrogen Timing in Winter Wheat

1: Report of County Experiments, East of Scotland College of Agriculture.
2: Report of Field Experiments and Surveys, East of Scotland College of Agriculture.
3: Report of Field Experiments and Surveys, Scottish Agricultural College.

Appendix 9. Pesticides in Model[21].

Commercial Name		Active Ingredient	Type	Cost per unit of active ingredient
1	Rovral	iprodione	Fungicide	11.40
2	Opoguard	terbuthylazine & terbutyn	Herbicide	9.32
3	Reglone	diquat	Herbicide	8.40
4	Du-Ter 50	fentin hydroxide	Fungicide	17.85
5	Fubol	mancozeb & metalaxyl	Fungicide	18.50
6	Aphox	pirimicarb	Insecticide	33.00
7	Gramoxone	paraquat	Herbicide	5.24
8	Bavistin	carbendazim	Fungicide	7.45
9	Sportak	prochloraz	Fungicide	18.75
10	Butisan	metazachlor	Herbicide	21.40
11	Pilot	quizalofop-ethyl	Herbicide	149.30
12	Corbel	fenpropimorph	Fungicide	19.20
13	Dorin & Cyclocel	triademenol, tridemorph, & chlormequat	Fungicide	21.06
14	Mecoprop & Ally	mecoprop & metsulfuron-methyl	Herbicide	4.78
15	Calixin	tridemorph	Fungicide	17.90
16	Chandor	linuron & trifluralin	Herbicide	2.75
17	Tilt	propiconazole	Fungicide	34.00
18	Treflan	trifluralin	Herbicide	3.47
19	Harmony M	thifensulfuron methyl & metsulfuron methyl	Herbicide	276.33
20	Punch C	carbendazim & flusilazole	Fungicide	51.84

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[21] The UK Pesticide Guide (1995). CAB International.

Appendix 10. Workable Hours (hours. month^{-1})

Region		Kinloss											
Soil		‘1’			‘2’			‘3’			‘4’		
Climate		‘0’	‘1’	‘2’	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’
Cultivate	Jan	225.	144.	171.	219.	144.	171.	213.	144.	171.	207.	144.	171.
	Feb	189.	180.	198.	159.	156.	189.	129.	132.	180.	99.	108.	171.
	Mar	198.	234.	234.	156.	189.	234.	114.	144.	234.	72.	99.	234.
	Apr	225.	198.	216.	195.	168.	216.	165.	138.	216.	135.	108.	216.
	May	189.	243.	216.	189.	222.	213.	189.	201.	210.	189.	180.	207.
	Jun	144.	216.	162.	141.	216.	156.	138.	216.	150.	135.	216.	144.
	Jul	270.	189.	189.	270.	192.	189.	270.	195.	189.	270.	198.	189.
	Aug	234.	198.	252.	234.	198.	252.	234.	198.	252.	234.	198.	252.
	Sep	243.	162.	216.	243.	162.	216.	243.	162.	216.	243.	162.	216.
	Oct	234.	234.	270.	234.	219.	270.	234.	204.	270.	234.	189.	270.
	Nov	207.	252.	252.	207.	246.	252.	207.	240.	252.	207.	234.	252.
	Dec	234.	189.	252.	210.	135.	252.	186.	81.	252.	162.	27.	252.
Cultivate or Harvest	Jan	54.	108.	45.	60.	108.	42.	66.	108.	39.	72.	108.	36.
	Feb	45.	45.	36.	42.	45.	36.	39.	45.	36.	36.	45.	36.
	Mar	36.	18.	18.	36.	18.	18.	36.	18.	18.	36.	18.	18.
	Apr	27.	27.	54.	27.	36.	54.	27.	45.	54.	27.	54.	54.
	May	63.	18.	63.	60.	18.	63.	57.	18.	63.	54.	18.	63.
	Jun	99.	9.	36.	99.	12.	36.	99.	15.	36.	99.	18.	36.
	Jul	0.	54.	54.	0.	54.	54.	0.	54.	54.	0.	54.	54.
	Aug	27.	36.	27.	27.	39.	27.	27.	42.	27.	27.	45.	27.
	Sep	9.	63.	54.	9.	69.	54.	9.	75.	54.	9.	81.	54.
	Oct	27.	45.	9.	24.	45.	9.	21.	45.	9.	18.	45.	9.
	Nov	63.	18.	18.	63.	18.	18.	63.	18.	18.	63.	18.	18.
	Dec	18.	27.	0.	18.	18.	0.	18.	9.	0.	18.	0.	0.

Appendix 10. continued. Workable Hours (hours. month^{-1})

Region		Mylnefield											
Soil		‘1’			‘2’			‘3’			‘4’		
Climate		‘0’	‘1’	‘2’	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’
Cultivate	Jan	144.	81.	234.	117.	69.	201.	90.	57.	168.	63.	45.	135.
	Feb	54.	126.	225.	42.	90.	225.	30.	54.	225.	18.	18.	225.
	Mar	216.	144.	234.	150.	114.	174.	84.	84.	114.	18.	54.	54.
	Apr	243.	234.	180.	171.	213.	177.	99.	192.	174.	27.	171.	171.
	May	117.	189.	234.	117.	186.	234.	117.	183.	234.	117.	180.	234.
	Jun	162.	198.	126.	162.	198.	126.	162.	198.	126.	162.	198.	126.
	Jul	252.	135.	117.	252.	132.	117.	252.	129.	117.	252.	126.	117.
	Aug	234.	225.	234.	234.	219.	234.	234.	213.	234.	234.	207.	234.
	Sep	189.	171.	225.	186.	165.	225.	183.	159.	225.	180.	153.	225.
	Oct	243.	207.	180.	234.	201.	147.	225.	195.	114.	216.	189.	81.
	Nov	207.	225.	225.	138.	171.	171.	69.	117.	117.	0.	63.	63.
	Dec	171.	54.	207.	117.	36.	171.	63.	18.	135.	9.	0.	99.
Cultivate or Harvest	Jan	18.	36.	18.	12.	30.	21.	6.	24.	24.	0.	18.	27.
	Feb	0.	9.	0.	0.	9.	0.	0.	9.	0.	0.	9.	0.
	Mar	36.	45.	9.	27.	42.	9.	18.	39.	9.	9.	36.	9.
	Apr	18.	9.	36.	15.	9.	30.	12.	9.	24.	9.	9.	18.
	May	45.	36.	9.	45.	36.	9.	45.	36.	9.	45.	36.	9.
	Jun	9.	54.	99.	9.	54.	99.	9.	54.	99.	9.	54.	99.
	Jul	18.	27.	45.	18.	27.	45.	18.	27.	45.	18.	27.	45.
	Aug	18.	27.	27.	18.	27.	27.	18.	27.	27.	18.	27.	27.
	Sep	18.	27.	36.	18.	27.	36.	18.	27.	36.	18.	27.	36.
	Oct	27.	18.	18.	27.	18.	18.	27.	18.	18.	27.	18.	18.
	Nov	0.	18.	0.	0.	15.	0.	0.	12.	0.	0.	9.	0.
	Dec	18.	0.	9.	15.	0.	9.	12.	0.	9.	9.	0.	9.

Appendix 10 continued. Workable Hours (hours. month^{-1})

Region		Paisley											
Soil		'1'			'2'			'3'			'4'		
Climate		'0'	'1'	'2'	'0'	'1'	'2'	'0'	'1'	'2'	'0'	'1'	'2'
Cultivate	Jan	108.	144.	153.	93.	117.	102.	78.	90.	51.	63.	63.	0.
	Feb	162.	90.	99.	126.	60.	66.	90.	30.	33.	54.	0.	0.
	Mar	162.	99.	108.	108.	66.	72.	54.	33.	36.	0.	0.	0.
	Apr	234.	180.	180.	156.	123.	135.	78.	66.	90.	0.	9.	45.
	May	171.	198.	216.	165.	168.	195.	159.	138.	174.	153.	108.	153.
	Jun	225.	189.	180.	210.	174.	159.	195.	159.	138.	180.	144.	117.
	Jul	180.	207.	180.	177.	204.	180.	174.	201.	180.	171.	198.	180.
	Aug	189.	243.	234.	183.	219.	234.	177.	195.	234.	171.	171.	234.
	Sep	225.	126.	153.	204.	114.	129.	183.	102.	105.	162.	90.	81.
	Oct	162.	99.	162.	108.	66.	108.	54.	33.	54.	0.	0.	0.
	Nov	144.	63.	126.	96.	42.	84.	48.	21.	42.	0.	0.	0.
	Dec	36.	45.	144.	24.	30.	96.	12.	15.	48.	0.	0.	0.
Cultivate or Harvest	Jan	18.	27.	9.	12.	21.	9.	6.	15.	9.	0.	9.	9.
	Feb	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
	Mar	36.	9.	9.	30.	6.	6.	24.	3.	3.	18.	0.	0.
	Apr	9.	0.	0.	6.	0.	0.	3.	0.	0.	0.	0.	0.
	May	27.	45.	9.	27.	45.	9.	27.	45.	9.	27.	45.	9.
	Jun	9.	0.	27.	9.	0.	27.	9.	0.	27.	9.	0.	27.
	Jul	18.	0.	45.	18.	0.	45.	18.	0.	45.	18.	0.	45.
	Aug	18.	9.	0.	18.	9.	0.	18.	9.	0.	18.	9.	0.
	Sep	9.	36.	0.	9.	33.	0.	9.	30.	0.	9.	27.	0.
	Oct	27.	18.	0.	18.	12.	0.	9.	6.	0.	0.	0.	0.
	Nov	9.	27.	9.	6.	18.	6.	3.	9.	3.	0.	0.	0.
	Dec	0.	0.	27.	0.	0.	18.	0.	0.	9.	0.	0.	0.

Appendix 10 continued. Workable Hours (hours. month^{-1})

Region		Wick											
Soil		‘1’			‘2’			‘3’			‘4’		
Climate		‘0’	‘1’	‘2’	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’
Cultivate	Jan	261.	189.	252.	258.	138.	198.	255.	87.	144.	252.	36.	90.
	Feb	126.	162.	225.	108.	108.	195.	90.	54.	165.	72.	0.	135.
	Mar	171.	279.	261.	114.	243.	222.	57.	207.	183.	0.	171.	144.
	Apr	243.	261.	216.	180.	204.	168.	117.	147.	120.	54.	90.	72.
	May	216.	252.	207.	189.	210.	207.	162.	168.	207.	135.	126.	207.
	Jun	162.	234.	144.	153.	216.	144.	144.	198.	144.	135.	180.	144.
	Jul	171.	207.	162.	171.	207.	162.	171.	207.	162.	171.	207.	162.
	Aug	243.	252.	243.	231.	252.	234.	219.	252.	225.	207.	252.	216.
	Sep	234.	216.	270.	216.	216.	246.	198.	216.	222.	180.	216.	198.
	Oct	252.	261.	234.	210.	222.	171.	168.	183.	108.	126.	144.	45.
	Nov	243.	252.	243.	198.	192.	171.	153.	132.	99.	108.	72.	27.
	Dec	225.	189.	252.	156.	126.	168.	87.	63.	84.	18.	0.	0.
Cultivate or Harvest	Jan	18.	9.	0.	15.	6.	0.	12.	3.	0.	9.	0.	0.
	Feb	0.	36.	27.	0.	24.	27.	0.	12.	27.	0.	0.	27.
	Mar	0.	0.	18.	0.	0.	18.	0.	0.	18.	0.	0.	18.
	Apr	0.	0.	45.	0.	0.	42.	0.	0.	39.	0.	0.	36.
	May	18.	9.	72.	15.	9.	72.	12.	9.	72.	9.	9.	72.
	Jun	63.	27.	90.	63.	27.	90.	63.	27.	90.	63.	27.	90.
	Jul	54.	72.	72.	54.	72.	72.	54.	72.	72.	54.	72.	72.
	Aug	18.	27.	9.	18.	27.	9.	18.	27.	9.	18.	27.	9.
	Sep	9.	54.	0.	9.	54.	0.	9.	54.	0.	9.	54.	0.
	Oct	27.	0.	18.	21.	0.	18.	15.	0.	18.	9.	0.	18.
	Nov	18.	0.	9.	18.	0.	9.	18.	0.	9.	18.	0.	9.
	Dec	9.	0.	18.	6.	0.	12.	3.	0.	6.	0.	0.	0.

Appendix 11-1. Results of Base Runs. Crop Areas (hectares, 000's)

Region	Kinloss			Mylnefield			Paisley			Wick		
Climate	'0'	'1'	'2'	'0'	'1'	'2'	'0'	'1'	'2'	'0'	'1'	'2'
Grass	3.4	2.4	2.5	37.5	34.6	38.5	18.1	150.4	150.4	33.1	12.4	3.1
Grass / Clover	317.3	275.7	276.0	232.9	235.3	237.5	633.8	442.3	448.1	185.9	206.5	184.6
Spring Barley	7.4	7.3	7.2	30.4	30.1	11.6	4.3	4.0	0.0	0.0	0.0	0.0
Winter Barley	9.0	3.7	6.4	7.6	5.8	1.0	2.5	3.1	0.0	0.0	0.0	0.0
Winter Wheat	1.2	0.1	1.7	0.7	0.0	0.0	0.6	0.1	0.0	0.0	0.0	0.0
Potatoes	5.0	5.1	5.2	5.7	5.9	7.4	0.7	0.6	0.5	0.0	0.0	0.0
Vining Peas	4.1	3.9	4.4	6.7	5.9	5.8	1.1	1.2	0.9	0.0	0.0	0.0
Oil Seed Rape	4.1	3.4	3.9	6.0	6.2	6.8	1.1	0.4	0.1	0.0	0.0	0.0

Appendix 11-2. Results of Base Runs. Crop Yields[22] (tonnes. hectare^{-1})

Region	Kinloss			Mylnefield			Paisley			Wick		
Climate	'0'	'1'	'2'	'0'	'1'	'2'	'0'	'1'	'2'	'0'	'1'	'2'
Grass	4.8	4.7	4.8	4.9	5.4	5.2	5.1	5.3	5.6	4.7	4.7	4.4
Grass / Clover	3.6	3.5	3.5	3.7	4.1	3.9	3.8	3.9	4.1	3.5	3.6	3.3
Spring Barley	5.6	7.1	7.5	6.5	6.4	7.7	7.1	6.3	-	-	-	-
Winter Barley	9.0	9.0	7.9	11.9	8.1	9.4	13.0	7.8	-	-	-	-
Winter Wheat	3.8	4.4	6.0	5.9	-	-	8.6	8.5	-	-	-	-
Potatoes	15.6	21.0	22.7	19.3	22.0	19.3	20.3	24.5	24.1	-	-	-
Vining Peas	6.8	8.2	8.5	8.0	7.5	9.5	9.0	7.6	7.8	-	-	-
Oil Seed Rape	4.3	3.6	3.0	5.0	3.8	3.4	3.8	2.8	2.8	-	-	-

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[22] The crop yields are defined in tonnes DM hectare^{-1}except for potatoes which are defined as tonnes wet matter hectare^{-1}.

Appendix 11-3. Results of Base Runs. Labour (man days, 000’s)

	Region	Kinloss			Mylnefield			Paisley			Wick		
	Climate	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’	‘0’	‘1’	‘2’
Fixed & Overtime	‘Cattle and sheep’	331	295	292	242	242	241	457	351	394	186	187	144
	‘Dairy’	75	75	75	42	43	43	413	440	440	26	27	28
	‘Sheep’	44	20	17	82	82	82	269	269	269	81	84	84
	‘Cropping‘	365	365	442	749	922	1326	134	192	38	0	0	0
	‘Cropping and cattle’	44	52	48	85	106	122	15	29	21	0	0	0
Casual	‘Cattle and sheep’	41	34	33	34	34	34	63	41	50	26	24	17
	‘Dairy’	12	10	10	6	4	4	57	10	9	4	3	1
	‘Sheep’	6	3	7	11	11	11	34	34	34	11	11	11
	‘Cropping‘	69	55	79	139	129	109	15	5	55	0	0	0
	‘Cropping and cattle’	8	4	5	14	7	7	4	0	0	0	0	0

Appendix 11-4. Results of Sensitivity Analysis. Crop Areas (hectares, 000's)

	Region	Kinloss		Mylnefield		Paisley		Wick	
	Climate	‘0’	‘1’	‘0’	‘1’	‘0’	‘1’	‘0’	‘1’
	Grass	3.5	1.4	36.7	34.6	18.1	150.6	33.1	12.4
	Grass / Clover	317.4	276.4	233.3	235.3	633.5	446.4	185.9	206.5
	Spring Barley	8.0	7.6	28.1	30.1	4.7	4.0	0.0	0.0
Cash Crops = -15%	Winter Barley	9.7	7.4	8.6	6.2	2.7	2.8	0.0	0.0
Forage Crops=+0%	Winter Wheat	1.0	1.3	3.8	0.2	0.5	0.5	0.0	0.0
	Potatoes	4.9	5.2	6.4	7.1	0.8	0.7	0.0	0.0
	Vining Peas	4.3	4.5	6.9	6.1	1.1	1.3	0.0	0.0
	Oil Seed Rape	4.2	3.8	5.4	6.6	1.0	0.4	0.0	0.0
	Grass	3.5	1.0	38.2	34.6	18.1	150.6	33.1	12.4
	Grass / Clover	317.4	277.3	233.1	235.3	633.5	442.3	185.9	206.5
	Spring Barley	7.4	7.3	32.6	30.1	4.9	3.7	0.0	0.0
Cash Crops = +15%	Winter Barley	7.3	7.6	7.1	5.3	2.8	3.1	0.0	0.0
Forage Crops =+0%	Winter Wheat	1.5	5.1	0.0	0.0	0.4	1.2	0.0	0.0
	Potatoes	5.2	5.2	5.0	5.1	0.7	0.6	0.0	0.0
	Vining Peas	4.0	4.4	6.4	5.6	0.9	1.1	0.0	0.0
	Oil Seed Rape	3.9	3.9	6.1	6.2	1.0	0.4	0.0	0.0
	Grass	0.5	2.0	29.8	34.6	140.6	150.9	39.2	11.8
	Grass / Clover	321.1	274.6	240.2	235.3	511.0	452.1	179.8	207.2
	Spring Barley	7.4	10.1	30.1	30.1	4.8	4.1	0.0	0.0
Cash Crops = +0%	Winter Barley	9.4	7.3	7.2	6.0	2.9	3.0	0.0	0.0
Forage Crops=-15%	Winter Wheat	1.7	1.2	1.7	0.2	0.5	0.1	0.0	0.0
	Potatoes	5.1	5.2	6.0	6.1	0.7	0.6	0.0	0.0
	Vining Peas	4.3	4.4	7.2	5.8	1.0	1.2	0.0	0.0
	Oil Seed Rape	3.9	3.8	7.2	6.5	1.0	0.8	0.0	0.0
	Grass	0.1	1.2	25.9	34.6	52.9	151.0	42.7	12.9
	Grass / Clover	320.0	276.8	244.0	235.3	599.0	452.4	176.3	206.0
	Spring Barley	7.6	7.3	30.2	30.1	4.5	4.0	0.0	0.0
Cash Crops = +0%	Winter Barley	9.2	7.4	6.3	11.4	2.7	2.9	0.0	0.0
Forage Crops=+15%	Winter Wheat	1.2	1.1	1.0	0.0	0.6	0.0	0.0	0.0
	Potatoes	5.0	5.2	6.0	5.2	0.7	0.6	0.0	0.0
	Vining Peas	4.1	4.3	6.9	6.6	1.0	1.2	0.0	0.0
	Oil Seed Rape	4.1	3.6	7.1	7.2	1.0	0.8	0.0	0.0

Appendix 11-5. Results of Sensitivity Analysis. Crop Yields[23] (tonnes. hectare^{-1})

	Region	Kinloss		Mylnefield		Paisley		Wick	
	Climate	‘0’	‘1’	‘0’	‘1’	‘0’	‘1’	‘0’	‘1’
Cash Crops = -15% Forage Crops=+0%	Grass	4.8	4.7	4.9	5.4	5.1	5.3	4.7	4.7
	Grass / Clover	3.6	3.5	3.7	4.1	3.8	3.9	3.5	3.6
	Spring Barley	5.1	6.4	5.8	5.7	6.2	5.6	-	-
	Winter Barley	8.7	7.9	10.4	7.2	11.4	7.0	-	-
	Winter Wheat	3.3	5.0	5.1	7.6	9.3	6.2	-	-
	Potatoes	13.3	17.9	16.4	18.7	17.2	20.8	-	-
	Vining Peas	5.9	7.1	7.0	6.5	7.8	6.6	-	-
	Oil Seed Rape	3.9	3.1	4.4	3.3	3.2	2.6	-	-
Cash Crops = +15% Forage Crops=+0%	Grass	4.8	4.7	4.9	5.4	5.1	5.3	4.7	4.7
	Grass / Clover	3.6	3.5	3.7	4.1	3.8	3.9	3.5	3.6
	Spring Barley	6.1	7.8	6.9	6.9	8.0	6.9	-	-
	Winter Barley	10.8	9.9	13.3	9.0	14.5	8.7	-	-
	Winter Wheat	4.2	8.3	-	-	11.6	9.1	-	-
	Potatoes	18.0	24.2	22.2	25.3	23.3	28.0	-	-
	Vining Peas	7.7	9.3	9.1	8.5	10.3	8.6	-	-
	Oil Seed Rape	4.8	4.1	5.5	4.2	4.2	3.3	-	-
Cash Crops = +0% Forage Crops=-15%	Grass	4.1	4.0	4.2	4.6	4.3	4.5	4.0	4.0
	Grass / Clover	3.1	3.0	3.1	3.5	3.2	3.3	3.0	3.1
	Spring Barley	5.6	7.1	6.5	6.4	7.1	6.3	-	-
	Winter Barley	9.8	9.0	11.6	8.0	12.9	7.8	-	-
	Winter Wheat	3.8	5.5	6.0	10.3	10.5	6.6	-	-
	Potatoes	15.6	21.0	19.3	22.0	20.3	24.4	-	-
	Vining Peas	6.8	8.2	8.0	7.5	9.0	7.6	-	-
	Oil Seed Rape	4.3	3.6	5.0	3.8	3.7	2.5	-	-
Cash Crops = +0% Forage Crops=+15%	Grass	5.5	5.4	5.6	6.2	5.9	6.1	5.4	5.4
	Grass / Clover	4.1	4.0	4.3	4.7	4.4	4.5	4.0	4.1
	Spring Barley	5.6	7.1	6.5	6.4	7.1	6.3	-	-
	Winter Barley	8.9	8.8	11.9	8.0	12.9	7.9	-	-
	Winter Wheat	3.8	6.2	5.9	-	10.4	8.8	-	-
	Potatoes	15.6	21.0	19.3	22.0	20.3	24.4	-	-
	Vining Peas	6.8	8.2	8.0	7.5	9.0	7.6	-	-
	Oil Seed Rape	4.3	3.6	5.0	3.8	3.7	2.6	-	-

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[23] The crop yields are defined in tonnes DM hectare^{-1}except for potatoes which are defined as tonnes wet matter hectare^{-1}.

Appendix 11-6. Results of Sensitivity Analysis. Labour (man days, 000's)

		Region	Kinloss		Mylnefield		Paisley		Wick	
		Climate	'0'	'1'	'0'	'1'	'0'	'1'	'0'	'1'
Cash Crops = -15% Forage Crops=+0%	Fixed & Overtime	'Cattle and sheep'	331	295	242	245	457	382	186	190
		'Dairy'	75	75	42	43	413	440	26	27
		'Sheep'	44	16	82	82	269	271	81	85
		'Cropping'	390	445	722	1091	137	200	0	0
		'Cropping and cattle'	47	53	81	109	16	23	0	0
	Casual	'Cattle and sheep'	41	34	34	34	64	48	26	26
		'Dairy'	12	11	6	5	56	10	4	3
		'Sheep'	6	4	11	12	35	35	11	11
		'Cropping'	58	76	121	107	13	4	0	0
		'Cropping and cattle'	7	6	16	4	3	0	0	0
Cash Crops = +15% Forage Crops=+0%	Fixed & Overtime	'Cattle and sheep'	331	295	242	245	457	375	186	189
		'Dairy'	75	75	42	43	414	440	26	27
		'Sheep'	44	17	82	82	269	270	81	85
		'Cropping'	385	508	1006	950	171	243	0	0
		'Cropping and cattle'	47	57	101	98	15	36	0	0
	Casual	'Cattle and sheep'	41	34	34	34	64	46	26	26
		'Dairy'	12	11	6	5	57	10	4	3
		'Sheep'	6	5	11	11	35	35	11	11
		'Cropping'	73	86	127	127	14	5	0	0
		'Cropping and cattle'	6	7	12	7	4	0	0	0

Appendix 11-6 continued. Results of Sensitivity Analysis. Labour (man days, 000's)

		Region	Kinloss		Mylnefield		Paisley		Wick	
		Climate	'0'	'1'	'0'	'1'	'0'	'1'	'0'	'1'
Cash Crops = +0% Forage Crops=-15%	Fixed & Overtime	'Cattle and sheep'	259	271	240	246	422	369	185	184
		'Dairy'	75	75	42	43	415	440	26	27
		'Sheep'	41	16	80	80	255	271	82	85
		'Cropping'	392	413	866	1001	165	218	0	0
		'Cropping and cattle'	45	50	87	108	16	27	0	0
	Casual	'Cattle and sheep'	27	29	33	34	56	45	26	25
		'Dairy'	12	11	6	7	56	10	4	3
		'Sheep'	6	5	11	11	33	35	12	11
		'Cropping'	63	81	126	122	14	5	0	0
		'Cropping and cattle'	8	7	13	7	4	0	0	0
Cash Crops = +0% Forage Crops=+15%	Fixed & Overtime	'Cattle and sheep'	331	298	242	245	457	365	186	194
		'Dairy'	75	76	43	43	414	440	27	27
		'Sheep'	44	23	82	82	269	270	81	85
		'Cropping'	392	474	866	1106	165	226	0	0
		'Cropping and cattle'	45	49	86	101	16	28	0	0
	Casual	'Cattle and sheep'	41	34	34	34	64	44	26	26
		'Dairy'	12	8	4	5	54	8	3	3
		'Sheep'	6	3	11	11	35	35	11	11
		'Cropping'	63	83	126	151	14	9	0	0
		'Cropping and cattle'	7	4	13	8	4	0	0	0

Appendix 11-7. Results of Sensitivity Analysis. End of Year Cash Position (£, 000,000’s).

	Region	Kinloss		Mylnefield		Paisley		Wick	
	Climate	‘0’	‘1’	‘0’	‘1’	‘0’	‘1’	‘0’	‘1’
Cash Crops = -15% Forage Crops=+0%	‘Cattle and sheep’	67.1	46.7	58.4	57.0	110.6	67.9	39.9	43.7
	‘Dairy’	20.1	18.6	12.2	12.1	103.7	77.7	5.8	4.0
	‘Sheep’	10.6	0.0	19.6	19.5	61.9	51.0	20.0	20.2
	‘Cropping‘	10.0	16.7	0.0	0.0	0.0	0.0	0.0	0.0
	‘Cropping and cattle’	4.0	4.4	7.7	7.7	1.9	1.3	0.0	0.0
Cash Crops = +15% Forage Crops=+0%	‘Cattle and sheep’	67.1	46.7	58.4	56.8	110.6	67.5	39.9	44.6
	‘Dairy’	20.8	19.6	12.2	12.1	111.2	83.0	5.9	4.0
	‘Sheep’	10.6	0.0	19.8	19.5	61.9	51.0	20.0	20.2
	‘Cropping‘	17.8	25.7	0.0	0.0	0.0	0.0	0.0	0.0
	‘Cropping and cattle’	4.3	10.2	8.8	8.9	3.5	2.6	0.0	0.0
Cash Crops = +0% Forage Crops=-15%	‘Cattle and sheep’	46.7	47.2	55.0	56.9	75.4	54.2	37.7	42.6
	‘Dairy’	20.2	21.3	12.2	12.1	99.2	84.2	5.8	4.0
	‘Sheep’	9.2	0.0	19.1	18.6	56.6	50.1	19.8	20.4
	‘Cropping‘	14.3	21.2	0.0	0.0	0.0	0.0	0.0	0.0
	‘Cropping and cattle’	4.1	5.1	8.7	8.6	2.3	1.4	0.0	0.0
Cash Crops = +0% Forage Crops=+15%	‘Cattle and sheep’	68.5	46.6	59.5	57.0	111.6	67.8	40.6	39.9
	‘Dairy’	20.8	17.2	12.4	12.1	106.3	86.5	6.3	4.1
	‘Sheep’	10.8	0.0	20.2	19.6	63.1	57.0	20.7	20.2
	‘Cropping‘	13.9	21.1	0.0	0.0	0.0	0.0	0.0	0.0
	‘Cropping and cattle’	4.2	4.5	9.0	8.4	2.5	1.4	0.0	0.0

Appendix 11-8. Results of Land Selling and Purchase Experiments. Sale and Purchase of Land (hectares, 000’s)

		Region	Kinloss		Mylnefield		Paisley		Wick	
		Climate	‘0’	‘1’	‘0’	‘1’	‘0’	‘1’	‘0’	‘1’
Animal Numbers = -15%	Purchased	‘Cattle and sheep’	0	0	0	0	0	0	0	0
		‘Dairy’	0	0	0	0	0	0	0	0
		‘Sheep’	0	0	0	0	0	0	0	0
		‘Cropping‘	6.1	0	0	0.3	0.1	0.4	-	-
		‘Cropping and cattle’	0	6.1	0	0	0	4.6	-	-
	Sold	‘Cattle and sheep’	3.5	3.4	0	0	0	0.9	0	0
		‘Dairy’	0.7	0.7	0	0	0	3.8	0	0
		‘Sheep’	0.3	2.1	0	0	0	0.3	0	0
		‘Cropping‘	0	0	0	0	0	0	-	-
		‘Cropping and cattle’	1.7	0	0	0.3	0.1	0	-	-
Animal Numbers = +0%	Purchased	‘Cattle and sheep’	0	0	0	0	0	0	0	0
		‘Dairy’	0	0	0	0	0	0	0	0
		‘Sheep’	0	0	0	0	0	0	0	0
		‘Cropping‘	2.2	4.2	1.7	0.4	0	0.4	-	-
		‘Cropping and cattle’	0	0.8	3.4	0	1.0	0.7	-	-
	Sold	‘Cattle and sheep’	0	4.5	4.3	0	0	0	0	0
		‘Dairy’	0	0.1	0.4	0.2	0	1.1	0	0
		‘Sheep’	2.2	0.4	0.5	0	1.0	0	0	0
		‘Cropping‘	0	0	0	0	0	0	-	-
		‘Cropping and cattle’	0	0	0	0.3	0	0	-	-

Appendix 11-8 continued. Results of Land Selling and Purchase Experiments. Sale and Purchase of Land (hectares, 000's)

		Region	Kinloss		Mylnefield		Paisley		Wick	
		Climate	'0'	'1'	'0'	'1'	'0'	'1'	'0'	'1'
Animal Numbers=+15%	Purchased	'Cattle and sheep'	0	0	0	0	0	0	0	0
		'Dairy'	0	0	0	0	0	0	0	0
		'Sheep'	0	0	0	0	0	0	0	0
		'Cropping'	6.0	6.9	0	0	0	0	0	0
		'Cropping and cattle'	0	0	0	0	0.2	0	0	0
	Sold	'Cattle and sheep'	3.4	3.4	0	0	0	0	0	0
		'Dairy'	0.7	1.0	0	0	0	0	0	0
		'Sheep'	0.2	1.3	0	0	0	0	0	0
		'Cropping'	0	0	0	0	0.2	0	0	0
		'Cropping and cattle'	1.8	1.2	0	0	0	0	0	0

Appendix 11-9. Results of Land Selling and Purchasing Experiments. Crop Areas (hectares, 000’s)

	Region	Kinloss		Mylnefield		Paisley		Wick	
	Climate	‘0’	‘1’	‘0’	‘1’	‘0’	‘1’	‘0’	‘1’
Animal Number=-15%	Grass	0.1	1.1	68.4	34.6	47.4	153.2	45.4	13.0
	Grass / Clover	315.8	273.5	202.3	235.3	559.4	421.0	173.6	148.8
	Spring Barley	7.2	11.4	18.9	4.7	2.1	5.7	0.0	0.0
	Winter Barley	8.6	1.4	5.3	0.9	1.8	1.9	0.0	0.0
	Winter Wheat	2.9	3.4	9.6	0.0	1.0	0.2	0.0	0.0
	Potatoes	6.4	4.1	5.5	6.9	0.6	0.9	0.0	0.0
	Vining Peas	5.2	2.6	7.0	5.2	1.0	1.4	0.0	0.0
	Oil Seed Rape	4.5	5.2	3.6	1.9	0.6	0.7	0.0	0.0
Animal Number=+0%	Grass	4.2	2.7	35.7	34.6	18.9	150.6	33.1	16.2
	Grass / Clover	315.6	271.2	230.7	235.2	632.5	452.0	185.9	202.8
	Spring Barley	8.2	11.5	23.9	6.5	1.6	3.6	0.0	0.0
	Winter Barley	6.7	6.7	1.1	0.7	0.9	2.4	0.0	0.0
	Winter Wheat	2.5	0.1	7.6	0.0	1.0	0.0	0.0	0.0
	Potatoes	3.6	1.9	6.2	6.0	1.0	0.6	0.0	0.0
	Vining Peas	1.9	2.6	13.3	8.0	1.1	1.2	0.0	0.0
	Oil Seed Rape	4.5	2.5	13.3	6.7	0.8	0.0	0.0	0.0
Animal Number=+15%	Grass	9.1	0.8	24.5	34.6	18.7	150.4	35.9	12.5
	Grass / Clover	307.2	272.4	246.1	235.3	633.5	446.8	183.1	149.3
	Spring Barley	6.8	11.4	21.6	18.6	0.5	2.4	0.0	0.0
	Winter Barley	9.7	2.8	0.9	0.6	1.4	1.6	0.0	0.0
	Winter Wheat	2.7	1.4	5.1	0.0	0.9	0.3	0.0	0.0
	Potatoes	6.6	6.1	9.1	7.1	0.6	0.6	0.0	0.0
	Vining Peas	5.2	1.5	3.5	2.6	1.2	1.1	0.0	0.0
	Oil Seed Rape	4.5	5.0	6.5	9.2	0.4	0.8	0.0	0.0

Appendix 11-10. Results of Base Runs. Crop Yields[24] (tonnes. hectare^{-1})

	Region	Kinloss		Mylnefield		Paisley		Wick	
	Climate	‘0’	‘1’	‘0’	‘1’	‘0’	‘1’	‘0’	‘1’
Animal Number=-15%	Grass	4.8	4.7	4.9	5.4	5.1	5.3	4.7	4.7
	Grass / Clover	3.6	3.5	3.7	4.1	3.8	3.9	3.5	3.6
	Spring Barley	5.6	7.1	6.5	6.4	7.1	6.3	-	-
	Winter Barley	9.0	9.0	11.9	8.1	13.0	7.8	-	-
	Winter Wheat	3.8	4.4	5.9	-	8.6	8.5	-	-
	Potatoes	15.6	21.0	19.3	22.0	20.3	24.5	-	-
	Vining Peas	6.8	8.2	8.0	7.5	9.0	7.6	-	-
	Oil Seed Rape	4.3	3.6	5.0	3.8	3.8	2.8	-	-
Animal Number=+0%	Grass	4.8	4.7	4.9	5.4	5.1	5.3	4.7	4.7
	Grass / Clover	3.6	3.5	3.7	4.1	3.8	3.9	3.5	3.6
	Spring Barley	5.6	7.1	6.5	6.4	7.1	6.3	-	-
	Winter Barley	9.0	9.0	11.9	8.1	13.0	7.8	-	-
	Winter Wheat	3.8	4.4	5.9	-	8.6	8.5	-	-
	Potatoes	15.6	21.0	19.3	22.0	20.3	24.5	-	-
	Vining Peas	6.8	8.2	8.0	7.5	9.0	7.6	-	-
	Oil Seed Rape	4.3	3.6	5.0	3.8	3.8	2.8	-	-
Animal Number=+15%	Grass	4.8	4.7	4.9	5.4	5.1	5.3	4.7	4.7
	Grass / Clover	3.6	3.5	3.7	4.1	3.8	3.9	3.5	3.6
	Spring Barley	5.6	7.1	6.5	6.4	7.1	6.3	-	-
	Winter Barley	9.0	9.0	11.9	8.1	13.0	7.8	-	-
	Winter Wheat	3.8	4.4	5.9	-	8.6	8.5	-	-
	Potatoes	15.6	21.0	19.3	22.0	20.3	24.5	-	-
	Vining Peas	6.8	8.2	8.0	7.5	9.0	7.6	-	-
	Oil Seed Rape	4.3	3.6	5.0	3.8	3.8	2.8	-	-

---

[24] The crop yields are defined in tonnes DM hectare^{-1}except for potatoes which are defined as tonnes wet matter hectare^{-1}.

Appendix 11-11. Results of Land Selling and Purchase Experiments. Labour (man days, 000’s)

		Region	Kinloss		Mylnefield		Paisley		Wick	
		Climate	‘0’	‘1’	‘0’	‘1’	‘0’	‘1’	‘0’	‘1’
Animal Numbers=-15%	Fixed & Overtime	‘Cattle and sheep’	291	315	212	212	404	365	163	180
		‘Dairy’	75	72	42	41	414	424	26	25
		‘Sheep’	43	18	78	81	258	269	78	84
		‘Cropping‘	225	162	945	1259	90	76	0	0
		‘Cropping and cattle’	49	80	78	76	17	27	0	0
	Casual	‘Cattle and sheep’	36	31	30	31	55	51	23	20
		‘Dairy’	9	6	7	36	52	0	5	3
		‘Sheep’	6	8	11	12	33	30	11	10
		‘Cropping‘	162	166	65	0	16	24	0	0
		‘Cropping and cattle’	5	5	16	5	4	3	0	0
Animal Numbers=+0%	Fixed & Overtime	‘Cattle and sheep’	325	298	237	249	448	369	182	163
		‘Dairy’	76	72	44	42	422	436	27	26
		‘Sheep’	44	19	82	86	268	272	81	89
		‘Cropping‘	588	408	1176	1075	42	74	0	0
		‘Cropping and cattle’	66	47	87	100	16	29	0	0
	Casual	‘Cattle and sheep’	40	35	33	36	62	43	25	21
		‘Dairy’	10	16	4	5	50	0	4	5
		‘Sheep’	6	7	11	11	34	33	11	11
		‘Cropping‘	0	62	161	124	27	16	0	0
		‘Cropping and cattle’	7	12	17	0	2	0	0	0

Appendix 11-11 continued. Results of Land Selling and Purchase Experiments. Labour (man days, 000’s)

		Region	Kinloss		Mylnefield		Paisley		Wick	
		Climate	‘0’	‘1’	‘0’	‘1’	‘0’	‘1’	‘0’	‘1’
Animal Numbers=+15%	Fixed & Overtime	‘Cattle and sheep’	337	286	248	273	444	375	187	142
		‘Dairy’	78	76	45	20	432	463	28	27
		‘Sheep’	45	15	92	87	253	278	85	93
		‘Cropping‘	221	341	1394	783	53	125	0	0
		‘Cropping and cattle’	58	71	117	93	16	27	0	0
	Casual	‘Cattle and sheep’	42	33	35	41	61	47	26	13
		‘Dairy’	10	15	6	27	59	0	4	4
		‘Sheep’	6	7	13	12	32	34	12	12
		‘Cropping‘	217	49	0	186	0	8	0	0
		‘Cropping and cattle’	5	10	5	0	3	0	0	0

Appendix 11-12. Results of Land Selling and Purchasing Experiments.
End of Year Cash Position (£, 000,000’s).

	Region	Kinloss		Mylnefield		Paisley		Wick	
	Climate	‘0’	‘1’	‘0’	‘1’	‘0’	‘1’	‘0’	‘1’
Animal Number=-15%	‘Cattle and sheep’	57.1	39.1	45.7	47.7	84.3	56.0	33.8	21.2
	‘Dairy’	16.8	17.6	10.0	8.7	80.1	58.9	4.8	3.3
	‘Sheep’	9.0	0.0	16.9	16.6	52.1	45.0	16.6	17.1
	‘Cropping‘	21.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	‘Cropping and cattle’	3.4	4.5	6.6	0.0	2.8	0.2	0.0	0.0
Animal Number=+0%	‘Cattle and sheep’	69.0	53.3	60.2	64.8	113.9	75.8	41.1	31.2
	‘Dairy’	21.2	24.3	12.5	13.7	100.4	75.3	7.8	5.1
	‘Sheep’	10.9	0.0	20.3	22.3	63.8	56.8	20.6	23.0
	‘Cropping‘	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	‘Cropping and cattle’	6.0	6.4	17.8	0.0	1.6	1.6	0.0	0.0
Animal Number=+15%	‘Cattle and sheep’	69.7	51.6	61.5	70.4	110.9	75.6	41.2	31.1
	‘Dairy’	21.9	22.6	13.7	3.8	102.2	73.0	7.9	8.6
	‘Sheep’	10.9	0.0	21.7	23.1	59.5	58.3	20.9	24.3
	‘Cropping‘	21.3	9.6	0.0	0.0	0.0	0.0	0.0	0.0
	‘Cropping and cattle’	4.1	5.2	10.5	0.0	2.2	1.5	0.0	0.0

Appendix 12. Parallel and Serial Listings of Dantzig-Wolfe Decomposition Algorithm.

Both the parallel and serial programs are written in FORTRAN and can be linked to either OSL or ERGOL routines. The parallel version is run on either a Cray T3D or a SUN network and the serial version is run on a SUN.

Parallel Version

joint.F

```
C------------------------------------------------------------------
C     Combined program for Cray T3D or SUN network
C      The communication protocol is pvm.
C
      program t3d_driver
C
C------------------------------------------------------------------
      implicit none
      include 'my_defs.inc'
      integer  mytid,ptid,pe_n
C------------------------------------------------------------------
      call pvmfmytid(mytid)
#ifdef Cray
      call pvmfgetpe(mytid, pe_n)
      if (pe_n .gt. maxsub) goto 1000
#else
      call pvmfparent(ptid)

      if (ptid .eq. pvmnoparent) then
        pe_n = 0
      else
        pe_n = 1
      end if
#endif
      write(6,*) 'mytid = ',mytid,' pe_n = ',pe_n
      if (pe_n .eq. 0) then
        call master1
      else
        call slave1
      end if

 1000 continue

      call pvmfexit(info)
      if (info .ne. pvmOK) write(6,*)pe_n, 'pvm_exit  =', info

      stop
      end
```

master1.F

```
C------------------------------------------------------------------
C------------------------------------------------------------------
C
```

Serial Version

joint.F

```
C------------------------------------------------------------------
C     Combined programs.
C     Serial version, - does not use pvm
C                     - developed for SUNs.
      program driver
C
C------------------------------------------------------------------
      implicit none
      include 'my_defs.inc'
C------------------------------------------------------------------
      call master1

      stop
      end
```

master1.F

```
C------------------------------------------------------------------
C------------------------------------------------------------------
C
```

Parallel Version continued

```
C          Solves master problem associated
C                with Dantzig-Wolfe Decomposition
C
C
C               ---------------------
C               | d0 | d1_c | d2_c |
C               ---------------------
C                  | d1  |
C                  ----------------
C                       | d2  |
C                       ---------
C       J.D.Finlayson                 Parallel: Ver 1.0
C
C                                      7/4/95
C
C->>> ----------------------------------------------> DANTZIG_WOLF >>>
      SUBROUTINE Master1
C----------------------------------------------------------------
      implicit none
C  Include definitions
      include 'my_defs.inc'
C  Proposal number, name of proposal
      integer iprop, iname
C  Number of subproblems modified
      integer nmod
C  Define work space
      double precision dspace(dspace_m_mx)
C  Define communications variables
      integer master_tid
      integer slave_tid(maxsub)
#ifdef Cray
      real timef
#endif
C----------------------------------------------------------------
 9000 format('Process',i3,': Iteration ', i6, ' ', A24)
 9001 format('Process',i3,': Number of modified slaves      =',i16)
C----------------------------------------------------------------
C  Initialise Communications
C----------------------------------------------------------------
      call set_master(dspace)
      call m_init_comms(master_tid, slave_tid)
      iprop = 0
      iname = m_n_col
C----------------------------------------------------------------
C   Solve problem
C----------------------------------------------------------------
      do 10 imaster = 1, maxit
        nmod = 0
        call solve_master(dspace)
        call send_dual(slave_tid)
        call get_vector(dspace, nmod, iprop, iname, slave_tid)
#ifdef Cray
        write(6,  9000) my_prcs_n, imaster, timef()
        write(99, 9000) my_prcs_n, imaster, timef()
#else
        write(6,  9000) my_prcs_n, imaster, ctime(time())
        write(99, 9000) my_prcs_n, imaster, ctime(time())
#endif
        write(6, 9001) my_prcs_n, nmod
```

Serial Version continued

```
C          Solves master problem associated
C                with Dantzig-Wolf Decomposition
C
C
C               ---------------------
C               | d0 | d1_c | d2_c |
C               ---------------------
C                  | d1  |
C                  ----------------
C                       | d2  |
C                       ---------
C       J.D.Finlayson                 Serial: Ver 1.0
C
C                                      7/4/95
C
C->>> ----------------------------------------------> DANTZIG_WOLF >>>
      SUBROUTINE Master1
C----------------------------------------------------------------
      implicit none
C  Include definitions
      include 'my_defs.inc'
C  Proposal number, name of proposal
      integer iprop, iname
C  Number of subproblems modified
      integer nmod
C  Define work space
      double precision dspace(dspace_mx)
      integer my_prcs_n
C----------------------------------------------------------------
C  Initialise
C----------------------------------------------------------------
      call set_master(dspace, my_prcs_n)
      iprop = 1
      iname = m_n_col + 1
      nmod  = 0
C----------------------------------------------------------------
C   Solve problem
C----------------------------------------------------------------
      call solve_master(dspace, my_prcs_n)
      call slave1(dspace, iname)
      call get_vector(dspace, nmod, iprop, iname, my_prcs_n)
C----------------------------------------------------------------
C  Report status and completion time
C----------------------------------------------------------------
      call m_print_soln(dspace, nmod, my_prcs_n)

      return
      END
C-<<< ----------------------------------------------< DANTZIG_WOLF <<<



C-> ----------------------------------------------> set_master >>>
      SUBROUTINE set_master(dspace, my_prcs_n)
C----------------------------------------------------------------
      implicit none
      include 'my_defs.inc'
#ifdef ERGOL
      include 'ERGOLI.INC'
```

Parallel Version continued

```
      if (nmod.eq.0) goto 20
 10  continue
C-------------------------------------------------------------------
C  Report status and completion time
C-------------------------------------------------------------------
 20  continue
      call kill_slaves(slave_tid)
      call m_print_soln(dspace, nmod)

      return
      END
C-<<< ----------------------------------------------< DANTZIG_WOLF <<<



C->>> ------------------------------------------------> set_master >>>
      SUBROUTINE set_master(dspace)
C-------------------------------------------------------------------
      implicit none
      include 'my_defs.inc'
#ifdef ERGOL
      include 'ERGOLI.INC'
      Include 'ERGOLN.INC'
#else
      include '/usr/local/osl/ekkincf/OSLI'
      include '/usr/local/osl/ekkincf/OSLN'
#endif
C  Parameters
      double precision dspace(dspace_m_mx)
C  Functions
      character*3 wr_i_t_ch3
C  Local variables
      integer i_null
      double precision rl_null
      character*8 ch8_null
      integer ou_cn, type, add_convx
      character*8 nw_r_nm
#ifdef Cray
      real timef
#endif
C-------------------------------------------------------------------
 9000 format('Process',i3,': Start time =      ', A24)
 9001 format('Process',i3,': Reading ',a50)
 9002 format('Process',i3,': ',a22,i6)
C-------------------------------------------------------------------
      open(unit= 8, file=crnt_dir//'output/'//m_fl_nm//'.8')
      open(unit=99, file=crnt_dir//'output/'//'time.dat')
C-------------------------------------------------------------------
#ifdef Cray
      write(99, 9000) my_prcs_n, timef()
#else
      write(99, 9000) my_prcs_n, ctime(time())
#endif
      call ekkdsca(rtcod, dspace, dspace_m_mx, nmodel)
       if (rtcod.gt.0) call chkrt('M: dsca', rtcod)
      call ekkdscm(rtcod, dspace, 1, 1)
       if (rtcod.gt.0) call chkrt('M: dscm', rtcod)
      call ekkiget(rtcod, dspace, OSLI, OSLILN)
```

Serial Version continued

```
      include 'ERGOLN.INC'
#else
      include '/usr/local/osl/ekkincf/OSLI'
      include '/usr/local/osl/ekkincf/OSLN'
#endif
C  Parameters
      double precision dspace(dspace_mx)
      integer my_prcs_n
C  Functions
      character*3 wr_ch3
C  Local variables
      integer i_null
      double precision rl_null
      character*8 ch8_null
      integer ou_cn, type
      character*8 nw_r_nm
C-------------------------------------------------------------------
 9000 format('Process',i3,': Start time =      ', A24)
 9001 format('Process',i3,': Reading ',a50)
 9002 format('Process',i3,': ',a22,i6)
C-------------------------------------------------------------------
C determine if convexity rows need to be added to subproblem.
C If I have to do interupted runs, then the first time that
C the model is run, convexity rows need to be appended for
C each sub problem.  This is a one off step and once included
C convx.dat should include a single containing zero.
C-------------------------------------------------------------------
      open(unit=30,file=crnt_dir//'data/iter.dat')
      read(30,*) iter_n
      close(30)
      open(unit=30,file=crnt_dir//'data/region.dat')
      read(30,*) region
      close(30)
C-------------------------------------------------------------------
      open(unit= 8, file=crnt_dir//'output/'//m_fl_nm//'.8')
      open(unit=99, file=crnt_dir//'output/time.dat')
C-------------------------------------------------------------------
      my_prcs_n = 0
      write(99, 9000) my_prcs_n, ctime(time())
      call ekkdsca(rtcod, dspace, dspace_mx, nmodel)
       if (rtcod.gt.0) call chkrt(my_prcs_n, 'M: dsca', rtcod)
      call ekkdscm(rtcod, dspace, 1, 1)
       if (rtcod.gt.0) call chkrt(my_prcs_n, 'M: dscm', rtcod)
      call ekkiget(rtcod, dspace, OSLI, OSLILN)
       if (rtcod.gt.0) call chkrt(my_prcs_n, 'M: iget', rtcod)
C-------------------------------------------------------------------
C  defaults for solution print out
C-------------------------------------------------------------------
c     Normally IPRTINFOMASK = 255 gives row and column data,
c                             1023 gives all possible info
c     ILOGFREQ     =  1
c     ILOGLEVEL    =  29
c18/5/95  read indexed files formatted for ERGOL
c18/5/95     ERGOLI(80)  =  1
C-------------------------------------------------------------------
      IPRINTUNIT   =  8
      IPRTINFOMASK = 255
      ISOLMASK     =  16
```

Parallel Version continued

```
      if (rtcod.gt.0) call chkrt('M: iget', rtcod)
C-------------------------------------------------------------------
C  alter defaults for solution print out (include all values)
C-------------------------------------------------------------------
c IPRTINFOMASK =  255 gives row and column data,
c                    1023 gives all possible info
c    ILOGFREQ    =   1
c    ILOGLEVEL   =  29
c18/5/95  read indexed files formatted for ERGOL
c18/5/95      ERGOLI(80)  =   1
C-------------------------------------------------------------------
     IPRINTUNIT   =   8
     IPRTINFOMASK =  255
     ISOLMASK     =   16
     ILINELEN     =  150
C-------------------------------------------------------------------
C determine if convexity rows need to be added to subproblem.
C If I have to do interupted runs, then the first time that
C the model is run, convexity rows need to be appended for
C each sub problem.  This is a one off step and for subsequent
C runs these rows should not be included again.
C-------------------------------------------------------------------
     open(unit=30,file=crnt_dir//'data/convx.dat')
     read(30,*) add_convx
     close(30)
C-------------------------------------------------------------------

C  negative array values allow room in matrix for convexity rows
C  (for each subproblem) and activities (for succesive solutions to
C  each subproblem) to be added to master
C-------------------------------------------------------------------
     if (add_convx .eq. 1) then
      IMAXROWS = -maxsub
     end if
     IMAXCOLS = -maxprp
     call ekkiset(rtcod, dspace, OSLI, OSLILN)
      if (rtcod.gt.0) call chkrt('M: iset', rtcod)
     write(6, 9001) my_prcs_n, crnt_dir//'data/'//m_fl_nm//'.mps'
     open(unit=rd_cn, file=crnt_dir//'data/'//m_fl_nm//'.mps')
     type = 2
     call ekkmps(rtcod, dspace, rd_cn, type, ou_cn)
      if (rtcod.gt.0) call chkrt('M: mps', rtcod)
     close(rd_cn)
     call ekknget(rtcod, dspace, OSLN, OSLNLN)
      if (rtcod.gt.0) call chkrt('M: nget', rtcod)
     call ekkiget(rtcod, dspace, OSLI, OSLILN)
      if (rtcod.gt.0) call chkrt('M: iget', rtcod)
     if (add_convx .eq. 1) then
C-------------------------------------------------------------------
C  Add convexity rows to master
C-------------------------------------------------------------------
      m_n_row = INUMROWS
      write(6, 9002)my_prcs_n, 'Number of rows      = ',
INUMROWS
      write(6, 9002)my_prcs_n, 'Number of cols      = ', INUMCOLS
     write(6, 9002)my_prcs_n, 'Max number of rows  = ',
```

Serial Version continued

```
     ILINELEN     =  150
C-------------------------------------------------------------------
C  negative array values allow room in matrix for convexity rows
C  (for each subproblem) and activities (for succesive solutions to
C  each subproblem) to be added to master
C-------------------------------------------------------------------
     if (iter_n.eq.1 .and. region.eq.1) then
      IMAXROWS = -maxsub
     end if
     IMAXCOLS = -maxprp
     call ekkiset(rtcod, dspace, OSLI, OSLILN)
      if (rtcod.gt.0) call chkrt(my_prcs_n, 'M: iset', rtcod)
     write(6, 9001) my_prcs_n, crnt_dir//'data/'//m_fl_nm//'.mps'
     open(unit=rd_cn, file=crnt_dir//'data/'//m_fl_nm//'.mps')
     type = 2
     call ekkmps(rtcod, dspace, rd_cn, type, ou_cn)
      if (rtcod.gt.0) call chkrt(my_prcs_n, 'M: mps', rtcod)
     close(rd_cn)
     call ekknget(rtcod, dspace, OSLN, OSLNLN)
      if (rtcod.gt.0) call chkrt(my_prcs_n, 'M: nget', rtcod)
     call ekkiget(rtcod, dspace, OSLI, OSLILN)
      if (rtcod.gt.0) call chkrt(my_prcs_n, 'M: iget', rtcod)
C-------------------------------------------------------------------
     write(6,9002)my_prcs_n, 'Number of rows      = ', INUMROWS
     write(6,9002)my_prcs_n, 'Number of cols      = ', INUMCOLS
     write(6,9002)my_prcs_n, 'Max number of rows  = ',
IMAXROWS
     write(6,9002)my_prcs_n, 'Max number of cols  = ', IMAXCOLS
C-------------------------------------------------------------------
C  Add convexity rows to master
C-------------------------------------------------------------------
     if (iter_n.eq.1 .and. region.eq.1) then
      m_n_row = INUMROWS
      do 20 i = 1, maxsub
C-------------------------------------------------------------------
c dspace(NROWLOWER+m_n_row+i-1) =  1.0D000 is an equality
c dspace(NROWLOWER+m_n_row+i-1) = -1.0D031 is a >
c constraint
C-------------------------------------------------------------------
        dspace(NROWLOWER+m_n_row+i-1) =  1.0D000
        dspace(NROWUPPER+m_n_row+i-1) =  1.0D000
        call ekkrow(rtcod, dspace, 1, m_n_row+i, 0, rl_null,
   &                                  i_null)
         if (rtcod.gt.0) call chkrt(my_prcs_n, 'M: row', rtcod)
        nw_r_nm = 'CONV_'//wr_ch3(i)
        call ekkname(rtcod, dspace, 1, nw_r_nm, m_n_row+I, 0,
   &                             ch8_null, 1, 0)
         if (rtcod.gt.0) call chkrt(my_prcs_n, 'M: name', rtcod)
 20    continue
     else
      m_n_row = INUMROWS - maxsub
     end if
     m_n_col = INUMCOLS


     END
```

Parallel Version continued

```
   &                                          IMAXROWS
     write(6, 9002)my_prcs_n, 'Max number of cols  = ',
IMAXCOLS
     do 20 i = 1, maxsub
C---------------------------------------------------------------
c dspace(NROWLOWER+m_n_row+i-1) =  1.0D000 is an equality
c dspace(NROWLOWER+m_n_row+i-1) = -1.0D031 is a >
c constraint
C---------------------------------------------------------------
      dspace(NROWLOWER+m_n_row+i-1) =  1.0D000
      dspace(NROWUPPER+m_n_row+i-1) =  1.0D000
      call ekkrow(rtcod, dspace, 1, m_n_row+i, 0, rl_null,
   &                                     i_null)
       if (rtcod.gt.0) call chkrt('M: row', rtcod)
      nw_r_nm = 'CONV_'//wr_i_t_ch3(i)
      call ekkname(rtcod, dspace, 1, nw_r_nm, m_n_row+i, 0,
   &                                ch8_null, 1, 0)
       if (rtcod.gt.0) call chkrt('M: name', rtcod)
 20   continue
    else
     m_n_row = INUMROWS - maxsub
    end if
    m_n_col = INUMCOLS

    END
C-< ---------------------------------------------< set_master <<<



C-> --------------------------------------------> send_dual >>>
    SUBROUTINE send_dual(slave_tid)
C---------------------------------------------------------------
    implicit none
    include 'my_defs.inc'
C  Parameters
    integer slave_tid(maxsub)
C---------------------------------------------------------------
    call pvmfinitsend(PVMDEFAULT, info)
    call pvmfpack(pvm_i_ty, m_rtcod, 1, 1, info)
    call pvmfpack(REAL8, m_dual(1), n_vector, 1, info)
    do 10 i = 1, maxsub
     call pvmfsend(slave_tid(i), msg_dual, info)
 10  continue

    END
C-< --------------------------------------------< send_dual <<<



C-> -------------------------------------------> get_vector >>>
    SUBROUTINE get_vector(dspace, nmod, iprop, iname,
slave_tid)
C---------------------------------------------------------------
    implicit none
    include 'my_defs.inc'
#ifdef ERGOL
    include 'ERGOLI.INC'
    include 'ERGOLN.INC'
#else
```

Serial Version continued

```
C-< ---------------------------------------------< set_master <<<



C-> --------------------------------------------> get_vector >>>
    SUBROUTINE get_vector(dspace, nmod, iprop, iname,
   &                                            my_prcs_n)
C---------------------------------------------------------------
    implicit none
    include 'my_defs.inc'
#ifdef ERGOL
    include 'ERGOLI.INC'
    include 'ERGOLN.INC'
#else
    include '/usr/local/osl/ekkincf/OSLI'
    include '/usr/local/osl/ekkincf/OSLN'
#endif
C  Functions
    character*6 wr_ch6
C  Parameters
    integer nmod, iprop, iname, my_prcs_n
    double precision dspace(dspace_mx)
C  Local variables
    integer j
    double precision s_cost, rl_null
    character*8 ch8_null, nw_c_nm
C---------------------------------------------------------------
 9000 format('Process',i3,': receiving vector ',i4)
 9001 format('Process',i3,': ', i5, i8, g20.8)
 9002 format('Process',i3,': ', i5, ' --- C)', g20.8)
C---------------------------------------------------------------
    call ekkgtmi(rtcod, dspace, 1)
     if (rtcod.gt.0) call chkrt(my_prcs_n, 'M:  gtmi', rtcod)
    write(6, 9000) my_prcs_n, region
    if (nout.eq.-1) goto 20
    nmod = 1
C---------------------------------------------------------------
C  Include column and establish c row
C---------------------------------------------------------------
    s_cost = dw_vector(nout+1)
    call ekkiget(rtcod, dspace, OSLI, OSLILN)
     if (rtcod.gt.0) call chkrt(my_prcs_n,'M: iget', rtcod)
    call ekkcol(rtcod, dspace, 1, m_n_col+iprop, nout, dw_vector,
   &       mptr)
     if (rtcod.gt.0) call chkrt(my_prcs_n,'M: col ', rtcod)
    nw_c_nm = 'P_'//wr_ch6(iname)
    call ekkname(rtcod, dspace, 0, ch8_null, 1,
   &       1, nw_c_nm, m_n_col+iprop, 0)
     if (rtcod.gt.0) call chkrt(my_prcs_n,'M: name', rtcod)
    call ekknget(rtcod, dspace, OSLN, OSLNLN)

     if (rtcod.gt.0) call chkrt(my_prcs_n,'M: nget', rtcod)
    dspace(NOBJECTIVE+m_n_col+iprop-1) = s_cost
C---------------------------------------------------------------
C  Establish upper and lower bounds for new activity
C---------------------------------------------------------------
    dspace(NCOLLOWER+m_n_col+iprop-1) = 0.0D000
    dspace(NCOLUPPER+m_n_col+iprop-1) = 1.0D031
```

Parallel Version continued

```
      include '/usr/local/osl/ekkincf/OSLI'
      include '/usr/local/osl/ekkincf/OSLN'
#endif
C Functions
c     character*3 wr_i_t_ch3
      character*6 wr_i_t_ch6
C Parameters
      integer nmod, iprop, iname, slave_tid(maxsub)
      double precision dspace(dspace_m_mx)
C Local variables
      integer j
      double precision s_cost, rl_null
      character*8 ch8_null, nw_c_nm
C-----------------------------------------------------------------
 9000 format('Process',i3,': receiving vector ',i4)
 9001 format('Process',i3,': ', i5, i8, g20.8)
 9002 format('Process',i3,': ', i5, ' --- C)', g20.8)
C-----------------------------------------------------------------
      do 30 i = 1, maxsub
        write(6, 9000) my_prcs_n, i
        call pvmfrecv(slave_tid(i), msg_vector, info)
          if (info.lt.0) call chkrt('M:recv', info)
        call pvmfunpack(pvm_i_ty, nout, 1, 1, info)
          if (info.lt.0) call chkrt('M:unpack', info)
        call pvmfunpack(pvm_i_ty, mptr(1), n_vector, 1, info)
          if (info.lt.0) call chkrt('M:unpack', info)
        call pvmfunpack(REAL8, dw_vector(1), n_vector, 1, info)
          if (info.lt.0) call chkrt('M:unpack', info)
        iname = iname + 1
        if (nout.eq.-1) goto 20
        nmod = 1
        if (iprop.lt.maxprp) then
          iprop = iprop + 1
        else
C-----------------------------------------------------------------
C There would be code here to establish which non-basic
C column to overwrite
C-----------------------------------------------------------------
        end if
C-----------------------------------------------------------------
C Include column and establish c row
C-----------------------------------------------------------------
        s_cost = dw_vector(nout+1)
        call ekkiget(rtcod, dspace, OSLI, OSLILN)
          if (rtcod.gt.0) call chkrt('M: iget', rtcod)
        call ekkcol(rtcod, dspace, 1, m_n_col+iprop, nout, dw_vector,
     &      mptr)
          if (rtcod.gt.0) call chkrt('M: col ', rtcod)
        nw_c_nm = 'P_'//wr_i_t_ch6(iname)
        call ekkname(rtcod, dspace, 0, ch8_null, 1,
     &      1, nw_c_nm, m_n_col+iprop, 0)
          if (rtcod.gt.0) call chkrt('M: name', rtcod)
        call ekknget(rtcod, dspace, OSLN, OSLNLN)
          if (rtcod.gt.0) call chkrt('M: nget', rtcod)
        dspace(NOBJECTIVE+m_n_col+iprop-1) = s_cost
C-----------------------------------------------------------------
C Establish upper and lower bounds for new activity
C-----------------------------------------------------------------
        dspace(NCOLLOWER+m_n_col+iprop-1) = 0.0D000
```

Serial Version continued

```
C-----------------------------------------------------------------
C Write vector information to file
C-----------------------------------------------------------------
      do 10 j = 1, nout
        write(6, 9001) my_prcs_n, iprop, mptr(j), dw_vector(j)
 10   continue
      write(6, 9002) my_prcs_n, iprop, dw_vector(nout+1)

 20   continue

      call ekknwmt(rtcod, dspace, 2)
        if (rtcod.gt.0) call chkrt(my_prcs_n, 'M: nwmt', rtcod)

      END
C-< ----------------------------------------------< get_vector <<<


C-> -------------------------------------------> solve_master >>>
      SUBROUTINE solve_master(dspace, my_prcs_n)
C-----------------------------------------------------------------
      implicit none
      include 'my_defs.inc'
#ifdef ERGOL
      include 'ERGOLI.INC'
      include 'ERGOLN.INC'
      include 'ERGOLR.INC'
#else
      include '/usr/local/osl/ekkincf/OSLI'
      include '/usr/local/osl/ekkincf/OSLN'
      include '/usr/local/osl/ekkincf/OSLR'
#endif
C Parameters
      double precision dspace(dspace_mx)
      integer my_prcs_n
C Local variables
      integer alg
C-----------------------------------------------------------------
      call ekkiget(rtcod, dspace, OSLI, OSLILN)
        if (rtcod.gt.0) call chkrt(my_prcs_n, 'M: iget', rtcod)
      alg = 1
      call ekksslv(rtcod, dspace, alg, 1)
        if (rtcod.gt.0) call chkrt(my_prcs_n, 'M: sslv', rtcod)
cjajh 31/3/1995 this ekkprts call is temporary
c     call ekkprts(rtcod, dspace)
c       if (rtcod.gt.0) call chkrt(my_prcs_n, 'M: prts', rtcod)
      call ekkrget(rtcod, dspace, OSLR, OSLRLN)
        if (rtcod.gt.0) call chkrt(my_prcs_n, 'M: rget', rtcod)
      call ekkiget(rtcod, dspace, OSLI, OSLILN)
        if (rtcod.gt.0) call chkrt(my_prcs_n, 'M: iget', rtcod)
      call ekknget(rtcod, dspace, OSLN, OSLNLN)
        if (rtcod.gt.0) call chkrt(my_prcs_n, 'M: nget', rtcod)
C-----------------------------------------------------------------
C Move reduced costs for master into region
C-----------------------------------------------------------------
      m_rtcod = IPROBSTAT
      if (IPROBSTAT.le.0) then
        do 10 i = 1, m_n_row
          m_dual(i) = dspace(NROWDUALS + i-1)
 10     continue
```

Parallel Version continued

```
      dspace(NCOLUPPER+m_n_col+iprop-1) = 1.0D031
C-----------------------------------------------------------------
C  Write vector information to file
C-----------------------------------------------------------------
      do 10 j = 1, nout
        write(6, 9001) my_prcs_n, iprop, mptr(j), dw_vector(j)
 10   continue
      write(6, 9002) my_prcs_n, iprop, dw_vector(nout+1)
 20   continue
 30 continue

      call ekknwmt(rtcod, dspace, 2)
       if (rtcod.gt.0) call chkrt('M: nwmt', rtcod)

      END
C-< ----------------------------------------------< get_vector <<<


C-> ---------------------------------------------> solve_master >>>
      SUBROUTINE solve_master(dspace)
C-----------------------------------------------------------------
      implicit none
      include 'my_defs.inc'
#ifdef ERGOL
      include 'ERGOLI.INC'
      include 'ERGOLN.INC'
      include 'ERGOLR.INC'
#else
      include '/usr/local/osl/ekkincf/OSLI'
      include '/usr/local/osl/ekkincf/OSLN'
      include '/usr/local/osl/ekkincf/OSLR'
#endif
C  Parameters
      double precision dspace(dspace_m_mx)
C  Local variables
      integer iter, alg
C-----------------------------------------------------------------
 9000 format('Process',i3,': Master problem status        = ',i16)
 9001 format('Process',i3,': Master objective function     = ',g16.3)
C-----------------------------------------------------------------
      alg = 1
      call ekkiget(rtcod, dspace, OSLI, OSLILN)
       if (rtcod.gt.0) call chkrt('M: iget', rtcod)
      iter = IITERNUM
      call ekksslv(rtcod, dspace, alg, 1)
       if (rtcod.gt.0) call chkrt('M: sslv', rtcod)
cjajh 31/3/1995 this ekkprts call is temporary
c     call ekkprts(rtcod, dspace)
c      if (rtcod.gt.0) call chkrt('M: prts', rtcod)

      call ekkrget(rtcod, dspace, OSLR, OSLRLN)
       if (rtcod.gt.0) call chkrt('M: rget', rtcod)
      call ekkiget(rtcod, dspace, OSLI, OSLILN)
       if (rtcod.gt.0) call chkrt('M: iget', rtcod)
      call ekknget(rtcod, dspace, OSLN, OSLNLN)
       if (rtcod.gt.0) call chkrt('M: nget', rtcod)
C-----------------------------------------------------------------
C  Move reduced costs for master into region
C-----------------------------------------------------------------
      m_rtcod = IPROBSTAT
```

Serial Version continued

```
      else
C-----------------------------------------------------------------
C  If infeasible, use auxiliary region
C-----------------------------------------------------------------
       call chkrt(my_prcs_n, 'M:  aux', rtcod)
       do 20 i = 1, m_n_row
         m_dual(i) = dspace(NROWAUX + i-1)
 20    continue
      end if

      call ekkptmi(rtcod, dspace, 1)
       if (rtcod.gt.0) call chkrt(my_prcs_n, 'M: ptmi', rtcod)

      return
      END
C-< ---------------------------------------------< solve_master <<<



C-> ---------------------------------------------> m_print_soln >>>
      SUBROUTINE m_print_soln(dspace, nmod, my_prcs_n)
C-----------------------------------------------------------------
      implicit none
      include 'my_defs.inc'
#ifdef ERGOL
      include 'ERGOLI.INC'
      include 'ERGOLR.INC'
#else
      include '/usr/local/osl/ekkincf/OSLI'
      include '/usr/local/osl/ekkincf/OSLR'
#endif
C  Parameters
      double precision dspace(dspace_mx)
      integer nmod, my_prcs_n
C-----------------------------------------------------------------
 9000 format('Process',i3,': Calling ekkbcdo')
 9001 format('Process',i3,': Slave modified (1 = true)      = ',i16)
 9002 format('Process',i3,': Master problem status          = ',i16)
 9003 format('Process',i3,': Master objective function      =',g16.6)
 9004 format('Process',i3,': Completion time = ', A24)
C-----------------------------------------------------------------
C  write out data file (includes columns derived from slave
C  problems)
C-----------------------------------------------------------------
      if (nmod .ne. 0) then
       open(unit=16,file=crnt_dir//'data/'//m_fl_nm//'.mps')
       call ekkbcdo(rtcod,dspace,16,1,2)
        if (rtcod .ne. 0) call chkrt(my_prcs_n, 'eol_bcdo',rtcod)
       close(16)
      end if
C-----------------------------------------------------------------
C  echo solution
C-----------------------------------------------------------------
      call ekkiget(rtcod, dspace, OSLI, OSLILN)
       if (rtcod.gt.0) call chkrt(my_prcs_n, 'M: iget', rtcod)
      call ekkrget(rtcod, dspace, OSLR, OSLRLN)
       if (rtcod.gt.0) call chkrt(my_prcs_n, 'M: rget', rtcod)
      write(6,9001) my_prcs_n, nmod
      write(6,9002) my_prcs_n, IPROBSTAT
```

Parallel Version continued

```
      write(6, 9000) my_prcs_n, m_rtcod
      write(6, 9001) my_prcs_n, -ROBJVALUE
      if (m_rtcod.le.0) then
        do 10 i = 1, m_n_row
          m_dual(i) = dspace(NROWDUALS + i-1)
 10     continue
      else
C----------------------------------------------------------------
C  If infeasible, use auxiliary region
C----------------------------------------------------------------
        call chkrt('M:  aux', rtcod)
        do 20 i = 1, m_n_row
          m_dual(i) = dspace(NROWAUX + i-1)
 20     continue
      end if

      END
C-< ---------------------------------------------< solve_master <<<



C-> ---------------------------------------------> kill_slaves >>>
      SUBROUTINE kill_slaves(slave_tid)
C----------------------------------------------------------------
      implicit none
      include 'my_defs.inc'
C  Parameters
      integer slave_tid(maxsub)
C----------------------------------------------------------------
      m_rtcod = die
      call pvmfinitsend(PVMDEFAULT, info)
      call pvmfpack(pvm_i_ty, m_rtcod, 1, 1, info)
      call pvmfpack(REAL8, m_dual(1), n_vector, 1, info)
      do 10 i = 1, maxsub
       call pvmfsend(slave_tid(i), msg_dual, info)
 10   continue

      END
C-< ---------------------------------------------< kill_slaves <<<



C-> ---------------------------------------------> m_init_comms >>>
      SUBROUTINE m_init_comms(master_tid, slave_tid)
C----------------------------------------------------------------
      implicit none

      include 'my_defs.inc'

C  Parameter
      integer master_tid, slave_tid(maxsub)
C  Local variables
      integer numt, message
C  Abort processors
      logical abort_slave
#ifdef Cray
      real timef
#endif
C----------------------------------------------------------------
 9000 format('Process',i3,': Error in process ',i4,' error # ', i4)
 9001 format('Process',i3,': Master communications initialised')
```

Serial Version continued

```
      write(6,9003) my_prcs_n, -ROBJVALUE
      call ekkprts(rtcod, dspace)
       if (rtcod.gt.0) call chkrt(my_prcs_n, 'M: prts', rtcod)
C----------------------------------------------------------------
C  echo time
C----------------------------------------------------------------
      write(99, 9004) my_prcs_n, ctime(time())
      close( 8)
      close(99)

      END
C-< ---------------------------------------------< m_print_soln <<<


C-> ---------------------------------------------------> wr_ch3 >>>
      character*3 function wr_ch3(i)
C----------------------------------------------------------------
      integer i
C----------------------------------------------------------------
      wr_ch3 = char(48+mod(i/100, 10))//
     &         char(48+mod(i/10, 10))//
     &         char(48+mod(i, 10))
C----------------------------------------------------------------
      return
      END
C-< ---------------------------------------------------< wr_ch3 <<<


C-> ---------------------------------------------------> wr_ch6 >>>
      character*6 function wr_ch6(i)
C----------------------------------------------------------------
      integer i
C----------------------------------------------------------------
      wr_ch6 = char(48+mod(i/100000, 10))//
     &         char(48+mod(i/10000, 10))//
     &         char(48+mod(i/1000, 10))//
     &         char(48+mod(i/100, 10))//
     &         char(48+mod(i/10, 10))//
     &         char(48+mod(i, 10))
C----------------------------------------------------------------
      return
      END
C-< ---------------------------------------------------< wr_ch6 <<<
```

Parallel Version continued

```
C-----------------------------------------------------------------
C  enroll program with pvm, my_prcs_n identifies the processor
C-----------------------------------------------------------------
      call pvmfmytid(master_tid)
      my_prcs_n = 0
#ifdef Cray
        call pvmfgsize(PVMALL, numt)
        numt = numt - 1
        do 10 i=1, maxsub
         call pvmfgettid(PVMALL, i, slave_tid(i))
 10     continue
#else
C-----------------------------------------------------------------
C  to generate debugging information substitute
C  PVMDEFAULT with PVMDEFAULT+PVMDEBUG
C-----------------------------------------------------------------
        call pvmfspawn('joint.ex8', PVMDEFAULT, '*', maxsub,
     &                           slave_tid, numt)
#endif
      abort_slave = .false.
      if (numt.lt.0) then
        call chkrt('M:S:spawn', numt)
        abort_slave = .true.
      else if (numt.lt.maxsub) then
        call chkrt('M:P:spawn', numt)
        do 20 i=1, maxsub
          if (slave_tid(i).lt.0)write(6,9000)my_prcs_n,i,slave_tid(i)
 20     continue
        abort_slave = .true.
      end if
      do 30 i=1, maxsub
        call allocate_regions(slave_tid(i), i)
 30   continue
C-----------------------------------------------------------------
C  Check allocation of regions
C-----------------------------------------------------------------
      do 40 i = 1, maxsub
        call pvmfrecv(slave_tid(i), msg_init2, info)
        if (info.lt.0) then
          call chkrt('M:recv', info)
          abort_slave = .true.
        end if
        call pvmfunpack(pvm_i_ty, message, 1, 1, info)
        if (info.lt.0) then
          call chkrt('M:unpack', info)
          abort_slave = .true.
        else if (message.eq.die) then
          abort_slave = .true.
        end if
 40   continue
      if (abort_slave) then
        message = die
      else
        message = pvmOK
      end if
      call pvmfinitsend(PVMDEFAULT, info)
      call pvmfpack(pvm_i_ty, message, 1, 1, info)
      do 50 i = 1, maxsub
        call pvmfsend(slave_tid(i), msg_init3, info)
 50   continue
```

Serial Version continued

Parallel Version continued

```
      if (abort_slave) STOP
      write(6, *) my_prcs_n

      END
C-< ---------------------------------------------< m_init_comms <<<



C-> ------------------------------------------> allocate_regions >>>
      SUBROUTINE allocate_regions(slave_tid, f1)
C-----------------------------------------------------------------
      implicit none
      include 'my_defs.inc'
C  Parameters
      integer slave_tid, f1
C-----------------------------------------------------------------
      region = f1
      call pvmfinitsend(PVMDEFAULT, info)
       if (info.lt.0) call chkrt('M:initsend', info)
      call pvmfpack(pvm_i_ty, region, 1, 1, info)
       if (info.lt.0) call chkrt('M:pack', info)
      call pvmfpack(pvm_i_ty, m_n_row, 1, 1, info)
       if (info.lt.0) call chkrt('M:pack', info)
      call pvmfpack(pvm_i_ty, m_n_col, 1, 1, info)
       if (info.lt.0) call chkrt('M:pack', info)
      call pvmfsend(slave_tid, msg_init1, info)
       if (info.lt.0) call chkrt('M:send', info)

      END
C-< ------------------------------------------< allocate_regions <<<



C-> ---------------------------------------------> m_print_soln >>>
      SUBROUTINE m_print_soln(dspace, nmod)
C-----------------------------------------------------------------
      implicit none
      include 'my_defs.inc'
#ifdef ERGOL
      include 'ERGOLR.INC'
#else
      include '/usr/local/osl/ekkincf/OSLR'
#endif
C  Parameters
      double precision dspace(dspace_m_mx)
      integer nmod
#ifdef Cray
      real timef
#endif
C-----------------------------------------------------------------
 9000 format('Process',i3,': Calling ekkbcdo')
 9001 format('Process',i3,': Number of modified slaves      = ',i16)
 9002 format('Process',i3,': Number of iterations by master = ',i16)
 9003 format('Process',i3,': Maximum number of iterations   = ',i16)
 9004 format('Process',i3,': Master objective function      =',g17.3)
 9005 format('Process',i3,': Completion time = ', A24)
C-----------------------------------------------------------------
C  write out data file (includes columns derived from slave problems)
```

Serial Version continued

Parallel Version continued

```
C-----------------------------------------------------------------
      write(6, 9000) my_prcs_n
      open(unit=16,file=crnt_dir//'data/'//m_fl_nm//'.mps')
      call ekkbcdo(rtcod,dspace,16,1,2)
       if (rtcod .ne. 0) call chkrt('eol_bcdo',rtcod)
      close(16)
C-----------------------------------------------------------------
C  echo solution
C-----------------------------------------------------------------
      call ekkrget(rtcod, dspace, OSLR, OSLRLN)
       if (rtcod.gt.0) call chkrt('M: rget', rtcod)
      write(6, 9001) my_prcs_n, nmod
      write(6, 9002) my_prcs_n, imaster
      write(6, 9003) my_prcs_n, maxit
      write(6, 9004) my_prcs_n, -ROBJVALUE
      call ekkprts(rtcod, dspace)
       if (rtcod.gt.0) call chkrt('M: prts', rtcod)
C-----------------------------------------------------------------
C  echo time
C-----------------------------------------------------------------
#ifdef Cray
      write(99, 9005) my_prcs_n, timef()
#else
      write(99, 9005) my_prcs_n, ctime(time())
#endif
      close(8)
      close(99)

      END
C-< ---------------------------------------------< m_print_soln <<




C-> ---------------------------------------------> wr_i_t_ch3 >>>
      character*3 function wr_i_t_ch3(i)
C-----------------------------------------------------------------
      integer i
C-----------------------------------------------------------------
      wr_i_t_ch3 = char(48+mod(i/100, 10))//
     &     char(48+mod(i/10, 10))//
     &     char(48+mod(i, 10))
C-----------------------------------------------------------------
      return
      END
C-< ---------------------------------------------< wr_i_t_ch3 <<


C-> ---------------------------------------------> wr_i_t_ch6 >>>
      character*6 function wr_i_t_ch6(i)
C-----------------------------------------------------------------
      integer i
C-----------------------------------------------------------------
      wr_i_t_ch6 = char(48+mod(i/100000, 10))//
     &           char(48+mod(i/10000, 10))//
     &           char(48+mod(i/1000, 10))//
     &           char(48+mod(i/100, 10))//
     &           char(48+mod(i/10, 10))//
     &           char(48+mod(i, 10))
C-----------------------------------------------------------------
```

Serial Version continued

Parallel Version continued

```
      return
      END
C-< ------------------------------------------------< wr_i_t_ch6 <<
```

slave1.F

```
C------------------------------------------------------------------
C------------------------------------------------------------------
C
C          Solves slave problems associated with a Dantzig-Wolf
C                                     Decomposition
C
C
C          J.D.Finlayson                    Parallel: Ver 1.0
C                                            7/4/95
C
C->>> ------------------------------------> DANTZIG_WOLF_slave1
>>>
      SUBROUTINE Slave1
C------------------------------------------------------------------
      implicit none
C  Include definitions
      include 'my_defs.inc'
C  Communications variables
      integer my_tid, master_tid, islave
      integer mchang
C  Define working space
      double precision dspace(dspace_s_mx)
      integer s_n_col
      double precision s_c_row(s_c_max)
C  Proposal number
      integer iname
C  File number
      integer f_n
C------------------------------------------------------------------
C  Initialise communications
C------------------------------------------------------------------
      write(6, *) 'entering s_init_comms'
      call s_init_comms(my_tid, master_tid)
C------------------------------------------------------------------
C    Establish data
C------------------------------------------------------------------
      call set_slave(dspace, s_c_row, s_n_col, f_n)

      imaster = 0
      mchang = -1
      iname = m_n_col + region - maxsub
C------------------------------------------------------------------
C    Solve problem

C------------------------------------------------------------------
      do 20 islave = 1, 9999
        call pvmfrecv(master_tid, msg_dual, info)
        call pvmfunpack(pvm_i_ty, m_rtcod, 1, 1, info)
        call pvmfunpack(REAL8, m_dual(1), n_vector, 1, info)
          if(m_rtcod.eq.die) call close_down(dspace, my_tid, f_n)
        iname = iname + maxsub
        call process_slave(dspace, mchang, master_tid, s_c_row,
     1                        s_n_col, my_tid, iname, f_n)
```

Serial Version continued

slave1.F

```
C------------------------------------------------------------------
C------------------------------------------------------------------
C
C          Solves slave problems associated with a Dantzig-Wolf
C                                     Decomposition
C
C
C          J.D.Finlayson                    Parallel: Ver 1.0
C                                            7/4/95
C
C->>> ------------------------------------> DANTZIG_WOLF_slave1
>>>
      SUBROUTINE slave1(dspace, iname)
C------------------------------------------------------------------
      implicit none
C  Include definitions
      include 'my_defs.inc'
C  Proposal number, status variables
      integer iname
C  Define working space
      double precision dspace(dspace_mx)
      integer s_n_col
      double precision s_c_row(s_c_max)
C  File number, process number
      integer f_n, my_prcs_n
C------------------------------------------------------------------
C    Establish data and solve problem
C------------------------------------------------------------------
      my_prcs_n = region
      call set_slave(dspace, s_c_row, s_n_col, f_n, my_prcs_n)
      call process_slave(dspace, s_c_row, s_n_col, iname, f_n,
     &                              my_prcs_n)
      call close_down(dspace, f_n, my_prcs_n)

      return
      END
C-<<< ------------------------------------< DANTZIG_WOLF_Slave
<<<



C-> ------------------------------------------------> set_slave >>>
      SUBROUTINE set_slave(dspace, s_c_row, n_col, f_n,
my_prcs_n)
C------------------------------------------------------------------
      implicit none
      include 'my_defs.inc'
#ifdef ERGOL
      include 'ERGOLI.INC'
      include 'ERGOLN.INC'
#else
      include '/usr/local/osl/ekkincf/OSLI'
      include '/usr/local/osl/ekkincf/OSLN'
```

Parallel Version continued

```
     imaster = 1
 20  continue

     STOP
     END
C-<<< --------------------------------< DANTZIG_WOLF_Slave <<<



C-> ------------------------------------------------> set_slave >>>
     SUBROUTINE set_slave(dspace, s_c_row, n_col, f_n)
C-----------------------------------------------------------------
     implicit none
     include 'my_defs.inc'
#ifdef ERGOL
     include 'ERGOLI.INC'
     include 'ERGOLN.INC'
#else
     include '/usr/local/osl/ekkincf/OSLI'
     include '/usr/local/osl/ekkincf/OSLN'
#endif
C  Parameters
     integer n_col, f_n
     double precision dspace(dspace_s_mx), s_c_row(s_c_max)
C-----------------------------------------------------------------
     f_n = 2*(region-1) + 1
     open(unit=8, file=crnt_dir//'output/'//filename(f_n)//'.8')
     call get_file(dspace, f_n, 1)
C-----------------------------------------------------------------
C Get basis, if no basis to read in then call ekksslv with
C init=2, otherwise read in a basis and use init=0.
C-----------------------------------------------------------------
     open(unit=26, file=crnt_dir//'data/'//filename(f_n)//'.26')
     call ekkbasi(rtcod, dspace, 26)
      if (rtcod.gt.0) call chkrt('S: basi', rtcod)
     close(26)
     call ekkscal(rtcod,dspace)
      if (rtcod.gt.0) call chkrt('S: scal', rtcod)
C-----------------------------------------------------------------
     call ekkiget(rtcod, dspace, OSLI, OSLILN)
      if (rtcod.gt.0) call chkrt('S: iget', rtcod)
     call ekknget(rtcod, dspace, OSLN, OSLNLN)
      if (rtcod.gt.0) call chkrt('S: nget', rtcod)
     n_col = INUMCOLS
     do 10 I = 1, n_col
      s_c_row(i) = dspace(NOBJECTIVE+i-1)
 10  continue
C-----------------------------------------------------------------
C  alter defaults for solution print out
C  (include non zero activities and rows)
C-----------------------------------------------------------------
c    ILOGFREQ     = 1000, 1
c    ILOGLEVEL    =    1, 29
c    IPRTINFOMASK = 255
C-----------------------------------------------------------------
     IPRINTUNIT   =   8
     IPRTINFOMASK =   3
     ISOLMASK     =  16
     ILINELEN     = 150
```

Serial Version continued

```
#endif
C  Parameters
     double precision dspace(dspace_mx), s_c_row(s_c_max)
     integer n_col, f_n, my_prcs_n
C-----------------------------------------------------------------
     f_n = 2 * (region-1) + 1
     open(unit=12, file=crnt_dir//'output/'//filename(f_n)//'.8')
     call get_file(dspace, f_n, 2, my_prcs_n)
C-----------------------------------------------------------------
C Get basis, if no basis to read in then call ekksslv with
C init=2, otherwise read in a basis and use init=0.
C-----------------------------------------------------------------
     open(unit=26, file=crnt_dir//'data/'//filename(f_n)//'.26')
     call ekkbasi(rtcod, dspace, 26)
      if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: basi', rtcod)
     close(26)
     call ekkscal(rtcod,dspace)
      if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: scal', rtcod)
C-----------------------------------------------------------------
     call ekkiget(rtcod, dspace, OSLI, OSLILN)
      if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: iget', rtcod)
     call ekknget(rtcod, dspace, OSLN, OSLNLN)
      if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: nget', rtcod)
     n_col = INUMCOLS
     do 10 i = 1, n_col
      s_c_row(i) = dspace(NOBJECTIVE+i-1)
 10  continue
C-----------------------------------------------------------------
C  alter defaults for solution print out
C    ILOGFREQ     = 1000, 1
C    ILOGLEVEL    =    1, 29
C    IPRTINFOMASK =    3 (normally in slave1.F)
C                 =  255 (normally in master1.F)
C-----------------------------------------------------------------
     IPRINTUNIT   =  12
     IPRTINFOMASK = 255
     ISOLMASK     =  16
     ILINELEN     = 150
     call ekkiset(rtcod, dspace, OSLI, OSLILN)
      if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: iset', rtcod)
     call ekkptmi(rtcod, dspace, 2)
      if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: ptmi', rtcod)
C-----------------------------------------------------------------
C  Get coupling rows
C-----------------------------------------------------------------
     call get_file(dspace, f_n+1, 3, my_prcs_n)
     call ekkptmi(rtcod, dspace, 3)
      if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: ptmi', rtcod)

     END
C-< ------------------------------------------------< set_slave <<<



C-> ------------------------------------------------> process_slave >>>
     SUBROUTINE process_slave(dspace, s_c_row, n_col, iname,
    &                                             f_n, my_prcs_n)
C-----------------------------------------------------------------
     implicit none
```

Parallel Version continued

```
      call ekkiset(rtcod, dspace, OSLI, OSLILN)
       if (rtcod.gt.0) call chkrt('S: iset', rtcod)
      call ekkptmi(rtcod, dspace, 1)
       if (rtcod.gt.0) call chkrt('S: ptmi', rtcod)
C-----------------------------------------------------------------
C  Get coupling rows
C-----------------------------------------------------------------
      call get_file(dspace, f_n+1, 2)
      call ekkptmi(rtcod, dspace, 2)
       if (rtcod.gt.0) call chkrt('S: ptmi', rtcod)

      END
C-< -----------------------------------------------< set_slave <<<



C-> -------------------------------------------> process_slave >>>
      SUBROUTINE process_slave(dspace, mchang, master_tid,
     1                       s_c_row, n_col, my_tid, iname, f_n)
C-----------------------------------------------------------------
      implicit none
      include 'my_defs.inc'
#ifdef ERGOL
      include 'ERGOLI.INC'
      include 'ERGOLN.INC'
      include 'ERGOLR.INC'
#else
      include '/usr/local/osl/ekkincf/OSLI'
      include '/usr/local/osl/ekkincf/OSLN'
      include '/usr/local/osl/ekkincf/OSLR'
#endif
C  Parameters
      integer mchang, master_tid, n_col, my_tid, iname, f_n
      double precision dspace(dspace_s_mx), s_c_row(s_c_max)
C  Functions
      character*6 wr_i_t_ch6
C  Local variables
      integer s_rtcod, iter, alg, init
      double precision new_c_row(s_c_max), s_soln(s_c_max)
      character*8 nw_c_nm
C-----------------------------------------------------------------
      call process_c_row(dspace, new_c_row, s_c_row, n_col)
C-----------------------------------------------------------------
C  Solve slave problem
C-----------------------------------------------------------------
      call ekkiget(rtcod, dspace, OSLI, OSLILN)
       if (rtcod.gt.0) call chkrt('S: iget', rtcod)
      iter = IITERNUM
      alg = 1
      init = 0
      call ekksslv(rtcod, dspace, alg, init)
       if (rtcod.gt.0) call chkrt('S: sslv', rtcod)
      call ekkiget(rtcod, dspace, OSLI, OSLILN)
       if (rtcod.gt.0) call chkrt('S: iget', rtcod)
      call ekknget(rtcod, dspace, OSLN, OSLNLN)
       if (rtcod.gt.0) call chkrt('S: nget', rtcod)
      s_rtcod = IPROBSTAT
C-----------------------------------------------------------------
C  Add in proposal if possible
C-----------------------------------------------------------------
```

Serial Version continued

```
      include 'my_defs.inc'
#ifdef ERGOL
      include 'ERGOLI.INC'
      include 'ERGOLN.INC'
      include 'ERGOLR.INC'
#else
      include '/usr/local/osl/ekkincf/OSLI'
      include '/usr/local/osl/ekkincf/OSLN'
      include '/usr/local/osl/ekkincf/OSLR'
#endif
C  Parameters
      integer n_col, iname, f_n, my_prcs_n
      double precision dspace(dspace_mx), s_c_row(s_c_max)
C  Functions
      character*6 wr_ch6
C  Local variables
      logical new_proposal
      double precision crnt_obj,last_obj
      integer s_rtcod, soln_pos, alg, init
      double precision new_c_row(s_c_max), s_soln(s_c_max)
      character*8 nw_c_nm
      character*13 last_obj_fn
C-----------------------------------------------------------------
      call process_c_row(dspace, new_c_row, s_c_row,
     &                                         n_col,my_prcs_n)
C-----------------------------------------------------------------
C  Solve slave problem
C-----------------------------------------------------------------
      call ekkgtmi(rtcod, dspace, 2)
       if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: gtmi', rtcod)
      call ekkiget(rtcod, dspace, OSLI, OSLILN)
       if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: iget', rtcod)
      alg  = 1
      init = 0
      call ekksslv(rtcod, dspace, alg, init)
       if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: sslv', rtcod)
      call ekkiget(rtcod, dspace, OSLI, OSLILN)
       if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: iget', rtcod)
      call ekknget(rtcod, dspace, OSLN, OSLNLN)
       if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: nget', rtcod)
      s_rtcod = IPROBSTAT
C-----------------------------------------------------------------
C  check to see if slave objective has changed from previous
C  iteration. if last_obj = 0. then either it is the first
C  iteration or previous iteration was a ray.  In either
C  case then include new proposal.
C-----------------------------------------------------------------
      last_obj_fn = 'last_obj'//char(48+region)//'.dat'
      open(unit=30,file=crnt_dir//'data/'//last_obj_fn)
      if (iter_n.ne.1) then
       read(30,*) last_obj
       rewind(30)
      else
       last_obj = 0.0D0
      endif
      crnt_obj = 0.0D0
      if (s_rtcod.eq.0) then
C-----------------------------------------------------------------
C  Slave problem optimal
C-----------------------------------------------------------------
```

Parallel Version continued

```
   if (IITERNUM.ne.iter.or.mchang.ne.s_rtcod.or.s_rtcod.ne.0)
  1                                          then
     mchang = s_rtcod
     if (s_rtcod.eq.0) then
C-----------------------------------------------------------------
C  Slave problem optimal
C-----------------------------------------------------------------
       do 10 i = 1, n_col
         s_soln(i) = dspace(NCOLSOL+i-1)
 10      continue
     else
C-----------------------------------------------------------------
C  Unbounded, so create ray from auxiliary region
C-----------------------------------------------------------------
       call chkrt('S:  aux', 0)
       do 20 i = 1, n_col
         s_soln(i) = dspace(NCOLAUX+i-1)
 20      continue
     end if
C-----------------------------------------------------------------
C  Get cost of solution
C-----------------------------------------------------------------
     call ekkrget(rtcod, dspace, OSLR, OSLRLN)
       if (rtcod.gt.0) call chkrt('S: rget', rtcod)
C-----------------------------------------------------------------
C  Swap control data
C-----------------------------------------------------------------
     call ekkptmi(rtcod, dspace, 1)
       if (rtcod.gt.0) call chkrt('S: ptmi', rtcod)
     call ekkgtmi(rtcod, dspace, 2)
       if (rtcod.gt.0) call chkrt('S: gtmi', rtcod)
C-----------------------------------------------------------------
C  Get contribution in dw_vector
C-----------------------------------------------------------------
     call ekkgemv(rtcod, dspace, 1, 1.0D0, s_soln, 0.0D0,
dw_vector)
       if (rtcod.gt.0) call chkrt('S: gemv', rtcod)
C-----------------------------------------------------------------
C  Put control data back into dspace {may not need this one}
C-----------------------------------------------------------------
     call ekkptmi(rtcod, dspace, 2)
       if (rtcod.gt.0) call chkrt('S: ptmi', rtcod)
C-----------------------------------------------------------------
C  Pack down
C-----------------------------------------------------------------
     nout = 0
     do 30 i = 1, m_n_row
       if (abs(dw_vector(i)).gt.1.0D-9) then
         nout = nout + 1
         dw_vector(nout) = dw_vector(i)
         mptr(nout) = i
       end if
 30    continue
C-----------------------------------------------------------------
C  Add 1.0 in convexity row (unless a ray), include column in
C  master
C-----------------------------------------------------------------
     if (s_rtcod.eq.0) then
       nout = nout + 1
       dw_vector(nout) = 1.0D0
```

Serial Version continued

```
      soln_pos = NCOLSOL
    else
C-----------------------------------------------------------------
C  Unbounded, so create ray from auxiliary region
C-----------------------------------------------------------------
      call chkrt(my_prcs_n, 'S:  aux', 0)
      soln_pos = NCOLAUX
    endif
    do 10 i = 1, n_col
      s_soln(i) = dspace(soln_pos+i-1)
      crnt_obj=crnt_obj+(s_soln(i)*s_c_row(i))
 10  continue
    if ((abs(last_obj).le.1.0D-8).or.(abs(crnt_obj).le.1.0D-8).or.
   &                        (s_rtcod.ne.0)) then
      new_proposal = .true.
    else if (abs(last_obj - crnt_obj).gt.1.0D-8) then
      new_proposal = .true.
    else
      new_proposal = .false.
    endif
C-----------------------------------------------------------------
C  Add in proposal if possible
C-----------------------------------------------------------------
    if (new_proposal) then
      write(6,*)'new_proposal',crnt_obj
C-----------------------------------------------------------------
C  Update last_obj value
C-----------------------------------------------------------------
      write(30,*) crnt_obj
C-----------------------------------------------------------------
C  Swap control data
C-----------------------------------------------------------------
      call ekkptmi(rtcod, dspace, 2)
        if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: ptmi', rtcod)
      call ekkgtmi(rtcod, dspace, 3)

        if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: gtmi', rtcod)
C-----------------------------------------------------------------
C  Get contribution in dw_vector
C-----------------------------------------------------------------
      call ekkgemv(rtcod, dspace, 1, 1.0D0, s_soln, 0.0D0,
   &                           dw_vector)
        if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: gemv', rtcod)
C-----------------------------------------------------------------
C  Put control data back into dspace
C-----------------------------------------------------------------
      call ekkptmi(rtcod, dspace, 3)
        if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: ptmi', rtcod)
C-----------------------------------------------------------------
C  Pack down
C-----------------------------------------------------------------
      nout = 0
      do 20 i = 1, m_n_row
        if (abs(dw_vector(i)).gt.1.0D-9) then
          nout = nout + 1
          dw_vector(nout) = dw_vector(i)
          mptr(nout) = i
        end if
 20   continue
C-----------------------------------------------------------------
```

Parallel Version continued

```
      mptr(nout) = m_n_row + region
     end if
           nw_c_nm = 'P_'//wr_i_t_ch6(iname)
     dw_vector(nout+1) = 0.0D0
     do 40 i = 1, n_col
      dw_vector(nout+1)=dw_vector(nout+1)+(s_soln(i)*
   &                                          s_c_row(i))
      if (abs(s_soln(i)).gt.1.0D-9) then
       write(8,*)' s_soln : ', nw_c_nm, ' : ',s_soln(i),i
      end if
 40   continue
    else
     call ekkptmi(rtcod, dspace, 1)
      if (rtcod.gt.0) call chkrt('S: ptmi', rtcod)
     nout = -1
    end if
C-----------------------------------------------------------------
C  Send vector information to master
C-----------------------------------------------------------------
    call pvmfinitsend(PVMDEFAULT, info)
     if (info.lt.0) call chkrt('S:initsend', info)
    call pvmfpack(pvm_i_ty, nout, 1, 1, info)
     if (info.lt.0) call chkrt('S:pack', info)
    call pvmfpack(pvm_i_ty, mptr(1), n_vector, 1, info)
     if (info.lt.0) call chkrt('S:pack', info)
    call pvmfpack(REAL8, dw_vector(1), n_vector, 1, info)
     if (info.lt.0) call chkrt('S:pack', info)
    call pvmfsend(master_tid, msg_vector, info)
     if (info.lt.0) call chkrt('S:send', info)

    END
C <---------------------------------------------< process_slave <<<



C-> --------------------------------------------> process_c_row >>>
    SUBROUTINE process_c_row(dspace, new_c_row, s_c_row,
n_col)
C-----------------------------------------------------------------
    implicit none
    include 'my_defs.inc'
#ifdef ERGOL
    include 'ERGOLN.INC'
#else
    include '/usr/local/osl/ekkincf/OSLN'
#endif
C  Parameters
    integer n_col
    double precision dspace(dspace_s_mx), new_c_row(s_c_max)
    double precision s_c_row(s_c_max)
C  Local variables
    double precision dratio
C-----------------------------------------------------------------
 9000 format('c row ', i8, g12.4, g12.4)
C-----------------------------------------------------------------
    do 10 i = 1, n_col
     new_c_row(i) = s_c_row(i)
 10  continue
C-----------------------------------------------------------------
```

Serial Version continued

```
C  Add 1.0 in convexity row (unless a ray), include column in
C   master
C-----------------------------------------------------------------
     if (s_rtcod.eq.0) then
      nout = nout + 1
      dw_vector(nout) = 1.0D0

      mptr(nout) = m_n_row + region
     end if
           nw_c_nm = 'P_'//wr_ch6(iname)
     dw_vector(nout+1) = crnt_obj
     do 30 i = 1, n_col
      if (abs(s_soln(i)).gt.1.0D-9) then
       write(12,*)' s_soln : ', nw_c_nm, ' : ',s_soln(i),I
      end if
 30   continue
    else
     call ekkptmi(rtcod, dspace, 2)
      if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: ptmi', rtcod)
     nout = -1
    end if
    close(30)

    END
C <---------------------------------------------< process_slave <<<



C-> --------------------------------------------> process_c_row >>>
    SUBROUTINE process_c_row(dspace, new_c_row, s_c_row,
   &                                          n_col, my_prcs_n)
C-----------------------------------------------------------------
    implicit none
    include 'my_defs.inc'
#ifdef ERGOL
    include 'ERGOLN.INC'
#else

    include '/usr/local/osl/ekkincf/OSLN'
#endif
C  Parameters
    integer n_col, my_prcs_n
    double precision dspace(dspace_mx), new_c_row(s_c_max)
    double precision s_c_row(s_c_max)
C  Local variables
    double precision dratio
C-----------------------------------------------------------------
 9000 format('c row ', i8, g12.4, g12.4)
C-----------------------------------------------------------------
    do 10 i = 1, n_col
     new_c_row(i) = s_c_row(i)
 10  continue
C-----------------------------------------------------------------
C  If master not feasible, use a piece of the feasible objective
C-----------------------------------------------------------------
    if (m_rtcod.eq.0) then
     dratio = 1.0D0
    else
     dratio = 1.0D-8
```

Parallel Version continued

```
C  If master not feasible, use a piece of the feasible objective
C----------------------------------------------------------------
      if (m_rtcod.eq.0) then
       dratio = 1.0D0
      else
       dratio = 1.0D-8
c       dratio = 0.0d0
      end if
C----------------------------------------------------------------
C  Get coupling rows
C----------------------------------------------------------------
      call ekkgtmi(rtcod, dspace, 2)
       if (rtcod.gt.0) call chkrt('S: gtmi', rtcod)
C----------------------------------------------------------------
C  Change costs in subproblem
C----------------------------------------------------------------
      call ekkgemv(rtcod, dspace, 2, 1.0D0, m_dual, dratio,
     1                          new_c_row(1))
       if (rtcod.gt.0) call chkrt('S: gemv', rtcod)
C----------------------------------------------------------------
C  Put control data back into dspace {may not need this one ?}
C----------------------------------------------------------------
c     call ekkptmi(rtcod, dspace, 2)
c      if (rtcod.gt.0) call chkrt('S: ptmi', rtcod)
C----------------------------------------------------------------
C  Transfer results back to slave problem
C----------------------------------------------------------------
      call ekkgtmi(rtcod, dspace, 1)
       if (rtcod.gt.0) call chkrt('S: gtmi', rtcod)
      call ekknget(rtcod, dspace, OSLN, OSLNLN)
       if (rtcod.gt.0) call chkrt('S: nget', rtcod)
      do 20 i = 1, n_col
       dspace(NOBJECTIVE+i-1) = new_c_row(i)
 20   continue

      END
C <---------------------------------------------< process_c_row <<<



C-> ---------------------------------------------> s_init_comms >>>
      SUBROUTINE s_init_comms(my_tid, master_tid)
C----------------------------------------------------------------
C      implicit none
      include 'my_defs.inc'
C  Parameters
      integer my_tid, master_tid
C  Local variables
      integer message
C----------------------------------------------------------------
 8000 format('Process',i3,': communications initialised')
C----------------------------------------------------------------
      call pvmfmytid(my_tid)
#ifdef Cray
      call pvmfgettid(PVMALL, 0, master_tid)
#else
      call pvmfparent(master_tid)
#endif
      call pvmfrecv(master_tid, msg_init1, info)
```

Serial Version continued

```
c       dratio = 0.0d0
      end if
C----------------------------------------------------------------
C  Get coupling rows
C----------------------------------------------------------------
      call ekkgtmi(rtcod, dspace, 3)
       if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: gtmi', rtcod)
C----------------------------------------------------------------
C  Change costs in subproblem
C----------------------------------------------------------------
      call ekkgemv(rtcod, dspace, 2, 1.0D0, m_dual, dratio,
     1                          new_c_row(1))
       if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: gemv', rtcod)
C----------------------------------------------------------------
C  Put control data back into dspace
C----------------------------------------------------------------
      call ekkptmi(rtcod, dspace, 3)
       if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: ptmi', rtcod)
C----------------------------------------------------------------
C  Transfer results back to slave problem
C----------------------------------------------------------------
      call ekkgtmi(rtcod, dspace, 2)
       if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: gtmi', rtcod)
      call ekknget(rtcod, dspace, OSLN, OSLNLN)
       if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: nget', rtcod)
      do 20 i = 1, n_col
       dspace(NOBJECTIVE+i-1) = new_c_row(i)
 20   continue

      END
C <---------------------------------------------< process_c_row <<<



C-> ---------------------------------------------> get_file >>>
      SUBROUTINE get_file(dspace, f_n, ml_n, my_prcs_n)
C----------------------------------------------------------------
      implicit none
      include 'my_defs.inc'
#ifdef ERGOL
      include 'ERGOLI.INC'
#else
      include '/usr/local/osl/ekkincf/OSLI'
#endif
C  Parameters
      integer f_n, ml_n, my_prcs_n
      double precision dspace(dspace_mx)
C  Local variables
      integer ou_cn, type
C----------------------------------------------------------------
 8000 format('Process',i3,': Reading:',a30)
      call ekkdscm(rtcod, dspace, ml_n, 1)
       if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: dscm', rtcod)
      write(6, 8000)my_prcs_n,crnt_dir//'data/'//filename(f_n)//'.mps'
      open(unit=rd_cn, file=crnt_dir//'data/'//filename(f_n)//'.mps')
C----------------------------------------------------------------
c18/5/95      call ekkiget(rtcod, dspace, OSLI, OSLILN)
c18/5/95       if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: iget', rtcod)
C18/5/95      ERGOLI(80) = 1
```

Parallel Version continued

```
      call pvmfunpack(pvm_i_ty, region, 1, 1, info)
      call pvmfunpack(pvm_i_ty, m_n_row, 1, 1, info)
      call pvmfunpack(pvm_i_ty, m_n_col, 1, 1, info)
C-------------------------------------------------------------------
c  my_prcs_n used to identify processor number
C-------------------------------------------------------------------
      my_prcs_n = region
C-------------------------------------------------------------------
      message = pvmOK
      call pvmfinitsend(PVMDEFAULT, info)
      call pvmfpack(pvm_i_ty, message, 1, 1, info)
      call pvmfsend(master_tid, msg_init2, info)
C-------------------------------------------------------------------
      call pvmfrecv(master_tid, msg_init3, info)
      call pvmfunpack(pvm_i_ty, message, 1, 1, info)
      if (message.eq.die) STOP

      write(6, 8000) my_prcs_n

      END
C-< ------------------------------------------------< s_init_comms <<<



C-> ------------------------------------------------> get_file >>>
      SUBROUTINE get_file(dspace, f_n, ml_n)
C-------------------------------------------------------------------
      implicit none
      include 'my_defs.inc'
#ifdef ERGOL
      include 'ERGOLI.INC'
#else
      include '/usr/local/osl/ekkincf/OSLI'
#endif
C  Parameters
      integer f_n, ml_n
      double precision dspace(dspace_s_mx)
C  Local variables
      integer ou_cn, type
C-------------------------------------------------------------------
 8000 format('Process',i3,': Reading:',a30)
      if (ml_n .eq. 1) then
        call ekkdsca(rtcod, dspace, dspace_s_mx, nmodel)
         if (rtcod.gt.0) call chkrt('S: dsca', rtcod)
      endif
      call ekkdscm(rtcod, dspace, ml_n, 1)
      if (rtcod.gt.0) call chkrt('S: dscm', rtcod)
      write(6, 8000)my_prcs_n,crnt_dir//'data/'//filename(f_n)//'.mps'
      open(unit=rd_cn, file=crnt_dir//'data/'//filename(f_n)//'.mps')
C-------------------------------------------------------------------
      call ekkiget(rtcod, dspace, OSLI, OSLILN)
       if (rtcod.gt.0) call chkrt('S: iget', rtcod)
C18/5/95    ERGOLI(80) = 1
      call ekkiset(rtcod, dspace, OSLI, OSLILN)
       if (rtcod.gt.0) call chkrt('S: iset', rtcod)
C-------------------------------------------------------------------

      type     = 2

      call ekkmps(rtcod, dspace, rd_cn, type, ou_cn)
```

Serial Version continued

```
c18/5/95    call ekkiset(rtcod, dspace, OSLI, OSLILN)
c18/5/95     if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: iset', rtcod)
      type     = 2
      call ekkmps(rtcod, dspace, rd_cn, type, ou_cn)
       if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: mps ', rtcod)
      close(rd_cn)

      END
C-< ------------------------------------------------< get_file <<<



C-> ------------------------------------------------> close_down >>>
      SUBROUTINE close_down(dspace, f_n, my_prcs_n)
C-------------------------------------------------------------------
      implicit none
      include 'my_defs.inc'
#ifdef ERGOL
      include 'ERGOLR.INC'
#else
      include '/usr/local/osl/ekkincf/OSLR'
#endif
C  Parameters
      double precision dspace(dspace_mx)
      integer f_n, my_prcs_n
C-------------------------------------------------------------------
 8000 format('Process',i3,': Slave  objective function = ',g14.6)
 8001 format('Process',i3,': Slave complete ',a20)
C-------------------------------------------------------------------
C  rewrite basis (this is for interupted runs)
C-------------------------------------------------------------------
      call ekkgtmi(rtcod, dspace, 2)
       if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: gtmi', rtcod)
      open(unit=26, file=crnt_dir//'data/'//filename(f_n)//'.26')
      call ekkbaso(rtcod, dspace, 26, 1)
      close(26)
C-------------------------------------------------------------------
C  echo slave solution
C-------------------------------------------------------------------
      call ekkrget(rtcod, dspace, OSLR, OSLRLN)
       if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: rget', rtcod)
      write(6, 8000) my_prcs_n, -ROBJVALUE
      call ekkprts(rtcod, dspace)
       if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: prts', rtcod)
      call ekkptmi(rtcod, dspace, 2)
       if (rtcod.gt.0) call chkrt(my_prcs_n, 'S: ptmi', rtcod)

      close(12)
      write(6, 8001) my_prcs_n, filename(f_n)

      return
      END
C-< ------------------------------------------------< close_down <<<
```

Parallel Version continued

```
      if (rtcod.gt.0) call chkrt('S: mps ', rtcod)
     close(rd_cn)

     END
C-< -------------------------------------------------< get_file <<<

C-> -----------------------------------------------> close_down >>>
     SUBROUTINE close_down(dspace, my_tid, f_n)
C------------------------------------------------------------------
     implicit none
     include 'my_defs.inc'
#ifdef ERGOL
     include 'ERGOLR.INC'
#else
     include '/usr/local/osl/ekkincf/OSLR'
#endif
C  Parameters
     double precision dspace(dspace_s_mx)
     integer my_tid,f_n
C------------------------------------------------------------------
 8000 format('Process',i3,': Slave  objective function = ',g16.3)
 8001 format('Process',i3,': Slave complete ',a20)
C------------------------------------------------------------------
C  rewrite basis (this is for interupted runs on Cray)
C------------------------------------------------------------------
     call ekkgtmi(rtcod, dspace, 1)
      if (rtcod.gt.0) call chkrt('S: gtmi', rtcod)
     open(unit=26, file=crnt_dir//'data/'//filename(f_n)//'.26')
     call ekkbaso(rtcod, dspace, 26, 1)
     close(26)
C------------------------------------------------------------------
C  echo slave solution
C------------------------------------------------------------------
     call ekkrget(rtcod, dspace, OSLR, OSLRLN)
      if (rtcod.gt.0) call chkrt('S: rget', rtcod)
     write(6, 8000) my_prcs_n, -ROBJVALUE
     call ekkprts(rtcod, dspace)
      if (rtcod.gt.0) call chkrt('S: prts', rtcod)
     call ekkptmi(rtcod, dspace, 1)
      if (rtcod.gt.0) call chkrt('S: ptmi', rtcod)

     close(8)
     write(6, 8001) my_prcs_n, filename(f_n)

     STOP
     END
C-< -----------------------------------------------< close_down <<<
```

chkrt.F

```
C->>> -----------------------------------------------------> chkrt <<<
c Analyses the return code and prints appropriate messages for a
c routine name of 15 characters.
C
     subroutine chkrt(rn_nm, rt_cod)
     implicit none
     include 'my_defs.inc'
     character*15 rn_nm
```

Serial Version continued

chkrt.F

```
C->>> -----------------------------------------------------> chkrt <<<
c Analyses the return code and prints appropriate messages for a
c routine name of 15 characters.
C
     subroutine chkrt(my_prcs_n, rn_nm, rt_cod)
     implicit none
     include 'my_defs.inc'
     character*15 rn_nm
```

Parallel Version continued

```
      integer rt_cod
      integer rt_cod_div_100

      rt_cod_div_100 = rt_cod/100
      if (rt_cod_div_100 .eq. 0) then
        write(*, 9000)my_prcs_n, rn_nm
      else if (rt_cod_div_100 .eq. 1) then
        write(*, 9001)my_prcs_n, rn_nm
      else if (rt_cod_div_100 .eq. 2) then
        write(*, 9002)my_prcs_n, rn_nm
      else if (rt_cod_div_100 .eq. 3) then
        write(*, 9003)my_prcs_n, rn_nm
      end if
      return

 9000 format('Process',i3,': Info message issued during call to ', a)
 9001 format('Process',i3,': Warning issued during call to ', a)
 9002 format('Process',i3,': Error occurred during call to ', a)
 9003 format('Process',i3,': Severe error occurred during call to ', a)
      end
```

lc_fpvm3.INC

```
#ifdef Cray
#else
      subroutine pvmfgettid
      end
      subroutine pvmfgsize
      end
      subroutine pvmfgetpe
      end
      subroutine pvmftest
      end
#endif


      integer pvm_i_ty
      logical cray

C     SUN settings
      parameter (pvm_i_ty = INTEGER4)
      parameter (cray = .false.)
C      Cray settings
c     parameter (pvm_i_ty = INTEGER8)
c     parameter (cray = .true.)

c     character*28 crnt_dir
c     data crnt_dir /'/home/finlay1/pvm3/bin/SUN4/'/
      character*10 crnt_dir
      data crnt_dir /'/spare/jf/'/
```

Serial Version continued

```
      integer my_prcs_n
      integer rt_cod
      integer rt_cod_div_100

      rt_cod_div_100 = rt_cod/100
      if (rt_cod_div_100 .eq. 0) then
        write(*, 9000)my_prcs_n, rn_nm
      else if (rt_cod_div_100 .eq. 1) then
        write(*, 9001)my_prcs_n, rn_nm
      else if (rt_cod_div_100 .eq. 2) then
        write(*, 9002)my_prcs_n, rn_nm
      else if (rt_cod_div_100 .eq. 3) then
        write(*, 9003)my_prcs_n, rn_nm
      end if
      return

 9000 format('Process',i3,': Info message issued during call to ', a)
 9001 format('Process',i3,': Warning issued during call to ', a)
 9002 format('Process',i3,': Error occurred during call to ', a)
 9003 format('Process',i3,': Severe error occurred during call to ', a)
      end
```

lc_fpvm3.INC

```
      integer pvm_i_ty
      logical cray

C     SUN settings
      parameter (pvm_i_ty = INTEGER4)
      parameter (cray = .false.)
C      Cray settings
c     parameter (pvm_i_ty = INTEGER8)
c     parameter (cray = .true.)

c     character*28 crnt_dir
c     data crnt_dir /'/home/finlay1/pvm3/bin/SUN4/'/
      character*15 crnt_dir
      data crnt_dir /'/spare/finlay1/'/
c     character*14 crnt_dir
c     data crnt_dir /'/disk/finlay1/'/

      character*3 filename(8)
C 0
      data filename/'k02','k01',
     2             'm02','m01',
     3             'p02','p01',
     4             'w02','w01'/
```

Parallel Version continued

my_defs.INC

```
      include 'fpvm3.h'
      include 'lc_fpvm3.INC'

C     Allocate working space (OSL 4 000 000, ERGOL 5 000 000)
      integer dspace_s_mx
      parameter (dspace_s_mx = 4  000)
      integer dspace_m_mx
      parameter (dspace_m_mx =  4 000)
C  Maximum number of solution iterations
      integer maxit
      parameter (maxit = 5000)
C  Actual number of subproblem matrices
      integer maxsub
      parameter (maxsub = 4)
C  Maximum number of columns present in any of the subproblems
      integer s_c_max
      parameter (s_c_max = 700 00)
C  Maximum number of coupling rows
      integer n_vector
      parameter (n_vector = 200)

C  Maximum number of proposals
      integer maxprp
      parameter (maxprp = maxsub * maxit)

C  Message definitions
      integer die, msg_init1, msg_init2, msg_init3
      integer msg_dual, msg_vector
      parameter (die       = -2)
      parameter (msg_init1  =  1)
      parameter (msg_init2  =  2)
      parameter (msg_init3  =  3)
      parameter (msg_dual   =  4)
      parameter (msg_vector =  5)
C  Provide space for matrix + coupling rows
C  !! DO NOT ALTER !!
      integer nmodel
      parameter (nmodel = 2)
C  Read channel
      integer rd_cn
      parameter (rd_cn = 15)
C  Commonly used integer variables
      integer i, info, rtcod

C  Miscellaneous common blocks used for communication
      integer region, m_n_row, m_n_col
      common/cregion/region, m_n_row, m_n_col

      integer imaster
      common/nmaster/imaster

      integer m_rtcod, junkd
      double precision m_dual(n_vector)
      common/dual/junkd, m_rtcod, m_dual
```

Serial Version continued

my_defs.INC

```
C  my_defs.inc
      include 'fpvm3.h'
      include 'lc_fpvm3.INC'

C     Allocate working space (OSL 4 500 000, ERGOL 5 000 000)
      integer dspace_mx
      parameter (dspace_mx = 4 500 000)
C  Actual number of subproblem matrices
      integer maxsub
      parameter (maxsub = 4)
C  Maximum number of columns present in any of the subproblems
      integer s_c_max
      parameter (s_c_max = 70 000)
C  Maximum number of coupling rows
      integer n_vector
      parameter (n_vector = 100)

C  Maximum number of proposals
      integer maxprp
      parameter (maxprp = 1)

C  Read channel
      integer rd_cn
      parameter (rd_cn = 15)
C  Commonly used integer variables
      integer i, info, rtcod

C  Miscellaneous common blocks used for communication
      integer region, m_n_row, m_n_col
      common/cregion/region, m_n_row, m_n_col

      integer m_rtcod, junkd
      double precision m_dual(n_vector)
      common/dual/junkd, m_rtcod, m_dual

      integer nout, junkv
      integer mptr(n_vector)
      double precision dw_vector(n_vector)
      common/vector/junkv, nout, mptr, dw_vector

C  Provide space for master, slave + coupling rows
C  !! DO NOT ALTER !!
      integer nmodel
      parameter (nmodel = 3)

C  if (iter_n=1 and region=1) then
C  I need to add convexity rows to master.
      integer iter_n
      common/c_iter1/iter_n

C  Time variables
      character*24 ctime
      integer time
      real*4 ti
      common /cti/ti
```

Parallel Version continued

```
      integer nout, junkv
      integer mptr(n_vector)
      double precision dw_vector(n_vector)
      common/vector/junkv, nout, mptr, dw_vector

C Time variables
      character*24 ctime
      integer time
      real*4 ti
      common /cti/ti

C Miscellaneous
      integer my_prcs_n
      common/cmy_prcs_n/ my_prcs_n

      character*3 m_fl_nm
      data m_fl_nm/'r50'/

      character*3 filename(8)
      data filename/'k51','k50',
     2            'm51','m50',
     3            'p51','p50',
     4            'w51','w50'/
```

Serial Version continued

```
C Miscellaneous
      character*3 m_fl_nm
      data m_fl_nm/'mst'/
```