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LAND USE IN RURAL CUMBRIA:
A LINEAR PROGRAMMING MODEL

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PREFACE

The research presented here was done as part of a Ph.D thesis by Ian Bishop (University of Melbourne) while based at Merlewood during 1977. The results will be incorporated into Ian's thesis and therefore must not be used in any published form. However, any comments on the study would be welcomed by Ian and should be sent to him at:-

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During the course of the research, a number of individuals and organizations contributed to the data collection, analysis and interpretation, particularly through a Working Group which was set up during the year. Whilst the results do not represent the opinions or policies of any of these organisations, both Ian Bishop and ITE are particularly grateful to the following for their generous co-operation.

Cumbria County Council, through D. Donnison and R. S. Smith
Forestry Commission, through J. Voysey and M. Hart
Lake District Special Planning Board, through R. Forster
Ministry of Agriculture, Fisheries and Food, through J. Cowie and J. Wright
Stirling University, through M. Makower

It must be emphasised that the research described here is exploratory. It examines some of the ways in which information on land characteristics can be applied to land use planning, for example, in examining some of the consequences of alternative land use options. The results are not proposals for allocation of land.

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CONTENTS

1 INTRODUCTION

2 CUMBRIA

3 LINEAR PROGRAMMING

4 INPUTS AND OUTPUTS

4.1 Present Management

4.1.1 Inputs

4.1.2 Outputs

4.1.3 Associated Factors

4.2 Alternative Management

4.3 Reliability of Coefficients

5 RESULTS

5.1 Current Performance

5.2 Potential Performance

5.2.1 Restrictions on Land Use

5.2.2 Management Options

5.3 Trade-off Definition

5.3.1 Dual Variables

5.3.2 Parametric Analysis

5.4 Multiple Objective or Goal Programming

6 RELIABILITY OF RESULTS

6.1 Assumptions and Omissions

6.2 Sensitivity Analysis

6.2.1 Theory

6.2.2 Application

7 OTHER MODELLING OPTIONS

8 CONCLUSION

REFERENCES

APPENDIX 1. LABOUR AND ENERGY INPUT ANALYSIS

APPENDIX 2. ECONOMIC INTERPRETATION

TABLES

2.1 Some Cumbrian statistics

2.2 Description of land classes in Cumbria

2.3 Area of rural land by land class

2.4 Distribution of agricultural grades by land class

2.5 Land use options in each land class

2.6 Estimate of present distribution of land use by land class - Cumbria

2.7 Land use by land class - (a) National Parks
(b) North Pennines AONB

4.1 Distribution of vegetation groups by land class

4.2 Labour and energy inputs to vegetation groups

4.3 Labour and energy inputs to agricultural land by land class

4.4 Labour and energy inputs per unit of livestock

4.5 U.K. Forestry Commission fertiliser application rates

4.6 Labour requirement for various forestry practices

4.7 Labour and energy inputs to timber production

4.8 Site yield guides for the Forestry Commission North West England Conservancy

4.9 Soil classification and distribution by land class

4.10 Yield class by soil type and altitude

4.11 Altitude distribution in land classes 13-16

4.12 Estimation of yield class by land class

4.13 Relative productivities of agricultural grades under different uses

4.14 Grazing livestock units

4.15 Analysis of herd composition - (a) some assumptions
(b) some Cumbrian parishes

4.16 Analysis of flock composition - (a) some assumptions
(b) some Cumbrian parishes

4.17 Land class stocking rates

4.18 Livestock sale weights

4.19 Livestock produce per GLU

4.20 Comparison of relative land class productivities for dairying as derived from two sources

4.21 Productivity of cropping and horticulture by land class

4.22 Physical factors in ecological condition-by land class

4.23 Heterogeneity indices of vegetation groups

4.24 Assumed distribution of vegetation groups by agricultural grade

4.25 Results of ecological survey on Dinas Estate

4.26 Normalised measures of ecological conditions in different habitats

4.27 Coefficients of Ecological Value

4.28 Comparison of ecological values with scores from Dinas Estate

4.29 Recreational scores derived in Cumbria County Council survey

4.30 Attribute scoring table for recreational coefficients

4.31 Land use independent scores of recreational potential by land class

4.32 Land use dependent recreation scores

4.33 Modification of land use dependent recreational potential by usage patterns and land class

4.34 Coefficients of recreational potential

4.35 Addition inputs and outputs associated with upland pasture improvement

4.36 Coefficients of meat production

4.37 Coefficients of food energy production

4.38 Coefficients of energy consumption

4.39 Coefficients of labour requirement

4.40 Coefficients of milk and wool production

4.41 Set of recreational potential coefficients derived by halving the access/infrastructure scores of Table 4.30

5.1 Input and output levels for present land use distribution
(a) whole county
(b) parks and commons

5.2 Pay-off table with restricted land use options

5.3 Pay-off table with no land use restrictions

5.4 Effect of removal of restrictions on land use
(a) all factors, timber objective
(b) each objective function

5.5 Distribution of land use outside Parks and Commons giving
(a) maximum timber production
(b) maximum meat production

5.6 Impact on objectives of low intensity forestry under
(a) maximisation of timber production
(b) maximisation of meat production

5.7 Pay-off table for high intensity stock management and no land use restrictions

5.8 Dual variables relating food energy production to land class area

5.9 The approach to multi-objective interactive decision-making of Njkamp & Rietveld (1976)

6.1 Energy and labour in transportation

FIGURES

2.1 Cumbria - showing National Parks and North Pennines AONB

2.2 Cumbria - showing land classes

4.1 Stocking of parishes in GLU km^{-2} plotted against percentage of land in land class 1

4.2 Stocking of parishes in GLU km^{-2} plotted against percentage of land in land class 2

4.3 Stocking of parishes in GLU km^{-2} plotted against percentage of land in land class 3

4.4 Stocking of parishes in GLU km^{-2} plotted against percentage of land in land class 4

4.5 Stocking of parishes in GLU km^{-2} plotted against percentage of land in land class 5

4.6 Plot of predicted parish stocking potential (P) against rates determined from census returns (A)

4.7 Parishes in which predicted potential (P) and actual stocking (A) diverge by more than 35%

5.1 Trade-off curve for timber production and recreational potential

5.2 Trade-off curve for recreational potential and ecological value

5.3 Trade-off curve for energy input and food energy production

5.4 Reduction of potential food energy production as available land in particular classes decreases

5.5 Graphical representation of model results

5.6 Use of maps in result presentation

6.1 Probability distribution of score for one attribute in one land class

6.2 Probability distribution of three land classes

1. INTRODUCTION

A linear programming model is applied to rural Cumbria to examine the relationships between land-use patterns and the achievement of county objectives.

These objectives may be some or all of - high agricultural production, high forestry production, maintenance of rural employment, provision of quality recreation for large numbers of people, nature conservation, or (in a possible longer term) low energy consumption. In order to model their achievement it was necessary to assess the potential contribution to each objective of all the available land in the county.

This was achieved by assessing the productivity of each of 16 land classes into which the whole rural countryside had been classified (Bunce and Smith, 1978). The land in each class can be used for coniferous forest, deciduous forest, beef cattle, dairy cattle, cropping (wheat or potatoes) or sheep or allowed to remain as wilderness. Associated with each use is an input of labour and energy and the production of timber, meat, milk, food energy or wool characteristic of each land class. Also associated with each combination of land use and land class is a recreational potential and an ecological (or nature conservation) value of the land.

All of these things are of importance in county decision making especially in view of national objectives of self-sufficiency in food and a reduction in dependence on foreign timber. The problem is to increase production of these items without loss of recreational opportunities and conservation values of which Cumbria is an important national supplier.

The role of the Lake District and Yorkshire Dales National Parks, of the proposed Area of Outstanding Natural Beauty in the Pennines, and of Common Land in the achievement or frustration of these aims is examined by computing possible achievement levels with the land use constraints these definitions confer.

2. CUMBRIA

Cumbria is a county of low population and large area. Its character remains essentially rural and its outstanding visual appeal was sufficient cause for over one-third of the county to be conferred National Park status (Fig. 2.1). Cumbria, its character and problems are described in detail in 'Choices for Cumbria' (Fanstone and Himsworth, 1976). Some basic statistics are given in Table 2.1.

Naturally not all of Cumbria is available for rural enterprise. Major and minor towns, transportation links, natural and artificial lakes, sporting facilities etc all reduce the area being considered in this study. The total area considered was that measured as the sum of ...

- i areas being farmed as given in Agricultural Census returns
- ii areas of Forestry Commission or dedicated woodland
- iii all common land.

This was a total of 6245 km^2.

Cumbria occupies all or part of 7100 kilometre grid squares on the Ordnance Survey maps. Each of these squares has been classified by Bunce and Smith (1978) into one of 16 land classes. (Fig. 2.2). The classes are described in Table 2.2; from this point on class 7 is eliminated since it contains essentially no land suitable for uses being considered here. The total number of squares in each class is larger than the available rural land and the areas were adjusted as shown in Table 2.3.

The land in the land classes is certainly not homogeneous - some classes, particularly 4 and 11, contain many different land types - and to model them as homogeneous is to introduce a simplification and a cause for suspicion of any results. This will be considered further in Chapter 6. Some of the variability is clear from the distribution of Agricultural Land Service Grades (hereafter called agricultural grades) through the land classes (Table 2.4)

Pressures on land use already exist in Cumbria - hence the need for National Parks, Areas of Outstanding Natural Beauty (AONB), Sites of Special Scientific Interest (SSSI) and a substantial county planning department. The purpose of these designations is in general to preserve aspects of the land which would otherwise disappear under demand for more food and timber products. In particular the National Park charter specifies nature conservation and provision of recreation (in that order of priority) as the objectives of the parks.

Some products such as meat, milk and wool are less important in national strategic sense than timber and food energy, but are very important as sources of rural income as long as urban demand continues. Therefore, these are also included in the modelling exercise. Inputs to the land are labour and energy (as fertilizer, fuels, machinery etc). Job creation is already an important part of rural policy while energy conservation may become increasingly significant if supplies become very expensive or are being conserved in line with national policies.

Lowlands (defined here as land in land classes 1 to 8) occupy 64% of Cumbria and the major land uses available are forestry (coniferous, deciduous or mixed), livestock grazing (beef cattle, dairy cattle or sheep), and cropping (barley and oats for stock or wheat and potatoes for human consumption). Other rural uses such as mining or quarrying, poultry, pigs, orchards, flower growing are not large scale options in Cumbria in the foreseeable future (next 40 years) and their inclusion in the model would add complications without providing a great deal in results. At higher altitudes cropping and dairying become so uneconomic as to be disregarded while substantial investment in pasture improvement and the designation of wilderness become arguable options. Table 2.5 summarises the options.

Some areas are also important as water catchments to which some land uses are better suited than others. To some degree the likelihood of land becoming part of a water supply catchment will correlate with land class but this is difficult to assess and was not formally considered in this exercise.

Present distribution of land use by land class is not fully known. Forestry and woodland have been correlated and the total area of crops is known but the distribution of sheep and various types of cattle is uncertain. Table 2.6 gives a plausible split of land class by use.

As they are separately administered, the National Parks are subject to different priorities in land use planning. The current land use pattern in the parks and also in the large AONB proposed for the North Pennines is given in Table 2.7.

Areas of common land (which is almost entirely used for grazing at present) are included in Table 2.6 and 2.7 because under current legislation there is little scope for changing land use on the commons.

Table 2.1 Some Cumbrian statistics (from Fanstone and Himsworth, 1976)

Area	6,809	km^2
Population (mid '74)	475,700	
Population density	0.70	persons/hectare
Area-Lake District National Park	2,243	km^2
Yorkshire Dales National Park	213	km^2

Employees - by industrial group 1973 estimates

Agriculture*	6,908
Mining & quarrying	2,709
Manufacturing	71,349
Construction	11,488
Services	90,103

*Total farmers and workers over 14,400.

Table 2.2 Description of land classes in Cumbria

Land class	Altitude range (m)	Soil pH range	Land form	Land use
1	0-150	3.0-6.0	Gentle slopes, with a variety of detailed pattern reflecting a range of underlying geological formations.	Varies, mainly cattle, with some sheep and cereals.
2	75-150	3.5-6.5	Mainly level with low relief and limited variation.	Mainly beef and dairy cattle. Some arable. Small areas of woodland.
3	150-300	4.5-7.0	Mainly level with low relief and little variation.	Less arable and more permanent grassland than 2.
4	150-225	3.5-7.0	Very variable with many of the low lying fells presenting a wide variety of slopes and features such as small rock outcrops.	Very variable ranging from arable to neglected slopes and woodland, mainly sheep. Sometimes afforested.
5	0-75	3.5-7.0	Alluvial lowlands with little pronounced relief, except where outcrops emerge from the alluvium.	Much arable and leys with beef and dairy cattle predominating. Less densely populated than 2 and 3.
6	0-75	4.5-7.1	Alluvial lowlands with little pronounced relief.	Mainly pasture with some arable but particularly associated with built up land
7	0+	6.0-7.1	Mainly estuarine.	Grazing sheep on salt marsh
8	0+	4.5-7.1	Coastal varying from dunes to cliffs and low eroded moraines.	Pasture mainly for dairy and beef, but some arable.
9	300-450	3.0-4.5	Lower fells on fringe of the principal mountains, with usually rolling relief.	Mainly sheep grazing but contains much 'marginal' land.
10	225-450	3.5-6.5	Very variable mountainous land with variable slopes and rocky formations. Wide altitudinal range.	Mainly sheep grazing with much 'marginal' land.

Table 2.2 (continued)

Land class	Altitude range (m)	Soil pH range	Land form	Land use
11	150-300	3.5-6.0	Complex, rock outcrops on lower fells.	Varies, but mainly improved land with grazing for sheep and cattle. Sometimes afforested.
12	225-300	3.5-6.5	Gently rolling hill slopes at an intermediate elevation.	Extensively afforested moorlands.
13	375-600	3.0-5.0	Mainly steeper sides of the hills and valley bottoms.	Sheep grazing. Much 'marginal' land.
14	525+	3.0-4.5	High plateau-like tops of hills with rounded outlines. Relatively featureless compared with types 15 and 16.	Low intensity sheep grazing.
15	300-600	3.5-5.5	Steep mountain sides with wide range of rocky features.	Low intensity sheep grazing. Much protected land.
16	375+	3.0-6.0	Steep rocky fells and mountain summits.	Low intensity sheep grazing and recreational use with much protected land.

From Heal (1976) and Bunce and Smith (1978)

Table 2.3 Distribution of rural land in Cumbria

Land class	No. of grid squares	Rural area (km^2)	Other major uses*
1	895	800	Urban, lakes
2	782	710	Urban
3	539	500	
4	853	810	
5	774	700	Urban
6	284	135	Urban
7	147	0	Mud, sand
8	237	150	Mud, sand, urban
9	620	610	
10	359	330	
11	339	310	
12	278	250	
13	382	350	Edge squares
14	208	190	Edge squares
15	121	120	
16	282	280	
	7100	6245	

*General losses for roads, road verges etc.

Table 2.4 Summary of Agricultural Grades in relation to land classes

Land class	Agricultural Grade (%) 1	2	3	4	5	6	7
1	-	0	51	25	9	5	10
2	-	8	59	25	1	1	6
3	-	-	23	60	14	0	2
4	-	0	14	44	31	0	10
5	-	5	72	9	6	2	7
6	-	5	72	8	1	11	3
7	-	-	15	47	18	3	18
8	-	-	45	21	4	17	12
9	-	-	0	1	92	-	7
10	-	-	-	10	86	-	4
11	-	-	0	25	65	-	10
12	-	-	-	9	66	-	25
13	-	-	-	1	98	-	1
14	-	-	-	-	100	-	-
15	-	-	-	-	100	-	-
16	-	-	-	-	99	-	1

Agricultural Grades (MAFF, 1976)

1. Land with no limitations
2. Land with minor limitations
3. Land with moderate limitations
4. Land with severe limitations
5. Land with very severe limitations
6. Urban.
7. Non-agricultural use.

Table 2.5 Land use options in each land class

Land class	Use 1	2	3	4	5	6
1	S	H	B	D	C	L
2	S	H	B	D	C	L
3	S	H	B	D	C	L
4	S	H	B	D	C	L
5	S	H	B	D	C	L
6	S	H	B	D	C	L
8	S	H	B	D	C	L
9	S	H	B	B^1	L^1	L
10	S	H	B	D	L^1	L
11	S	H	B	D	L^1	L
12	S	H	B	D	L^1	L
13	S	H	B	B^1	L^1	L
14	S	W	B	-	-	L
15	S	H	B	B^1	L^1	L
16	S	W	B	-	-	L

S - Coniferous forest/Softwood
H - Deciduous forest/Hardwood
B - Beef cattle
B^1 - Beef cattle: improved pastures
D - Dairy cattle
C - Crops (Wheat and potatoes)
L - Sheep
L^1 - Sheep: improved pastures
W - Wilderness

Table 2.6 Estimate of present distribution of land use by land class-Cumbria

Land class	Use (km²) 1	2	3	4	5	6	Total	Common Land
1	22	27	116	500	25	110	800	24
2	11	24	180	400	5	90	710	5
3	10	8	190	82	10	200	500	24
4	45	20	200	45	-	500	810	62
5	10	24	100	450	16	100	700	22
6	2	6	13	100	14	-	135	-
8	1	3	26	100	-	20	150	14
9	50	6	154	-	-	400	610	259
10	8	4	13	5	-	300	330	100
11	20	6	70	34	-	180	310	77
12	82	4	43	-	-	120	250	60
13	4	-	26	-	-	320	350	161
14	1	-	-	-	-	189	190	134
15	3	-	17	-	-	100	120	72
16	5	-	-	-	-	265	280	165
Total	285	132	1148	1716	70	2894	6245	1179

Table 2.7 Land use of land class

(a) National Parks

Land class	Use (km^2) 1	2	3	4	5	6	Total	Common land
1	7	20	30	63	-	95	215	10
2	-	10	-	100	5	-	115	-
3	-	5	85	-	-	40	130	6
4	20	18	92	-	-	235	365	45
5	5	16	-	94	10	-	125	-
6	-	2	-	13	-	-	15	-
8	-	-	-	5	-	10	15	2
9	35	4	91	-	-	280	410	196
10	6	2	7	-	-	185	200	50
11	15	5	25	-	-	95	140	42
12	14	3	13	-	-	50	80	40
13	-	-	-	-	-	85	85	54
14	-	-	-	-	-	40	40	29
15	3	-	17	-	-	95	115	69
16	15	-	-	-	-	265	280	165
Total	120	85	360	275	15	1475	2330	708

(b) North Pennines AONB

2	-	-	-	5	-	-	5	-
3	-	-	75	-	-	25	100	4
4	-	-	-	-	-	35	35	7
9	-	-	30	-	-	60	90	33
10	5	-	-	-	-	105	110	30
11	-	-	15	-	-	40	55	15
12	-	-	-	-	-	15	15	10
13	-	-	26	-	-	229	255	105
14	1	-	-	-	-	149	150	105
15	-	-	-	-	-	5	5	5
Total	6	-	146	5	0	663	820	312

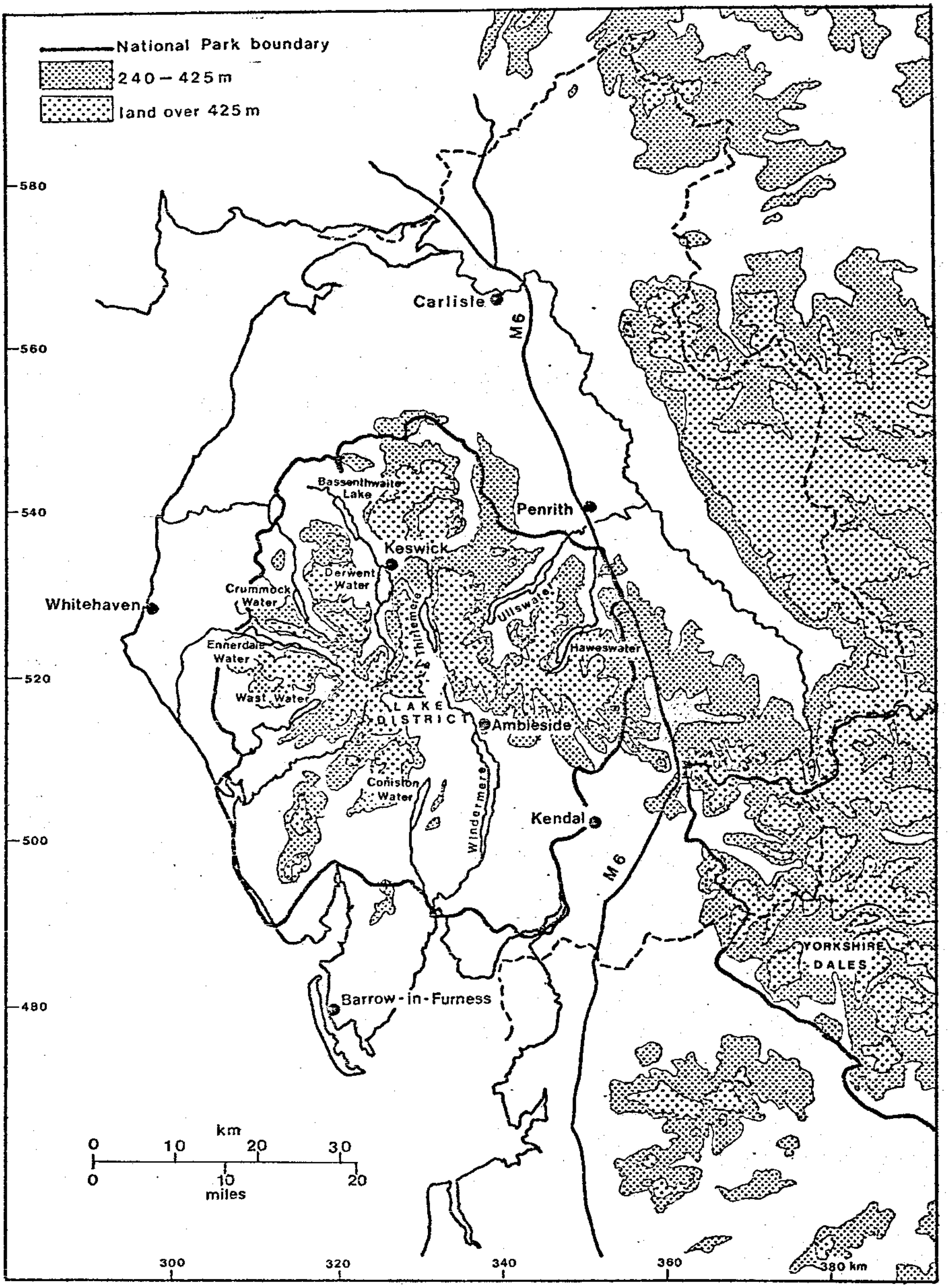


Fig 2.1 Cumbria - showing National Parks and North Pennines AONB.

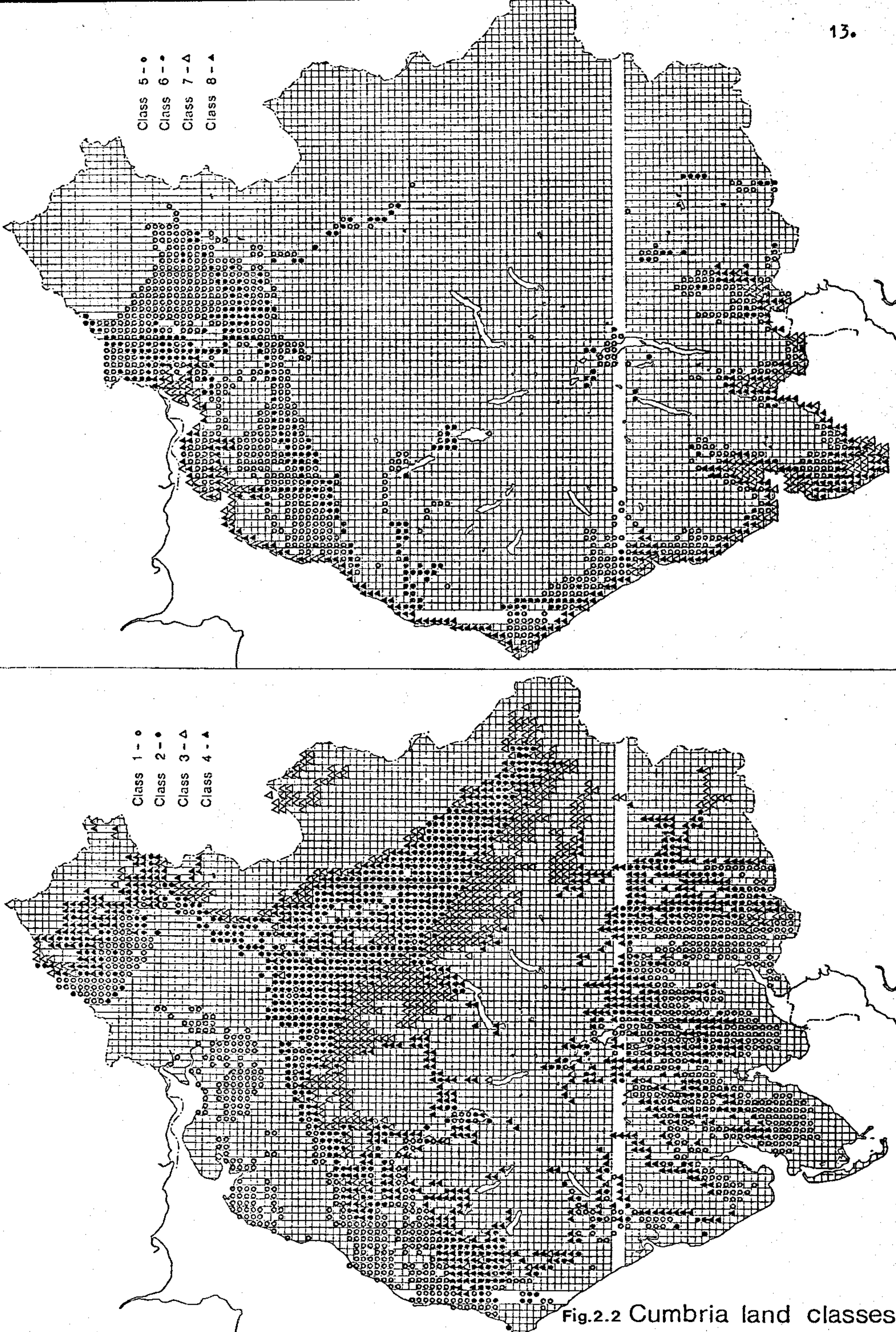
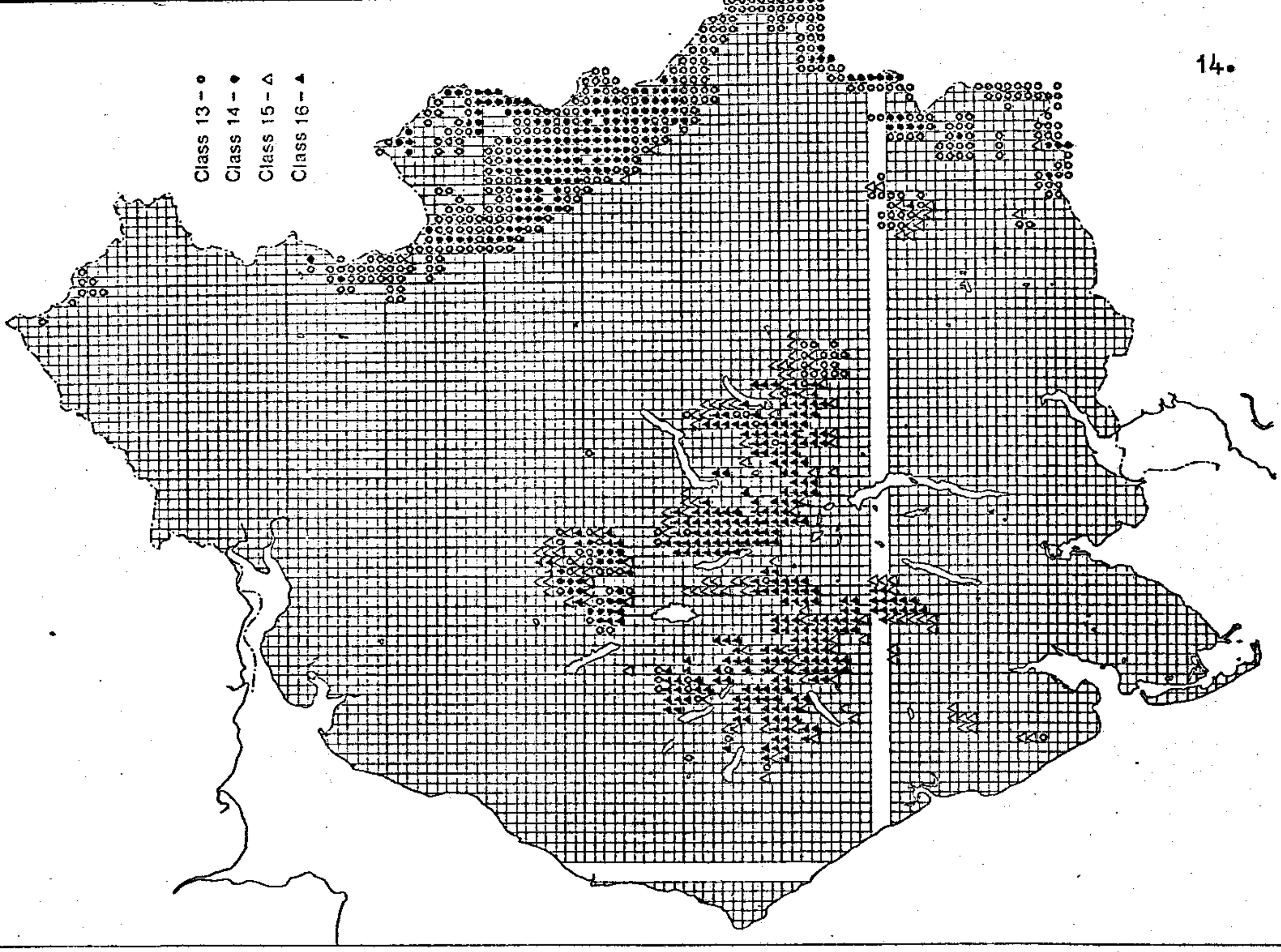


Fig.2.2 Cumbria land classes



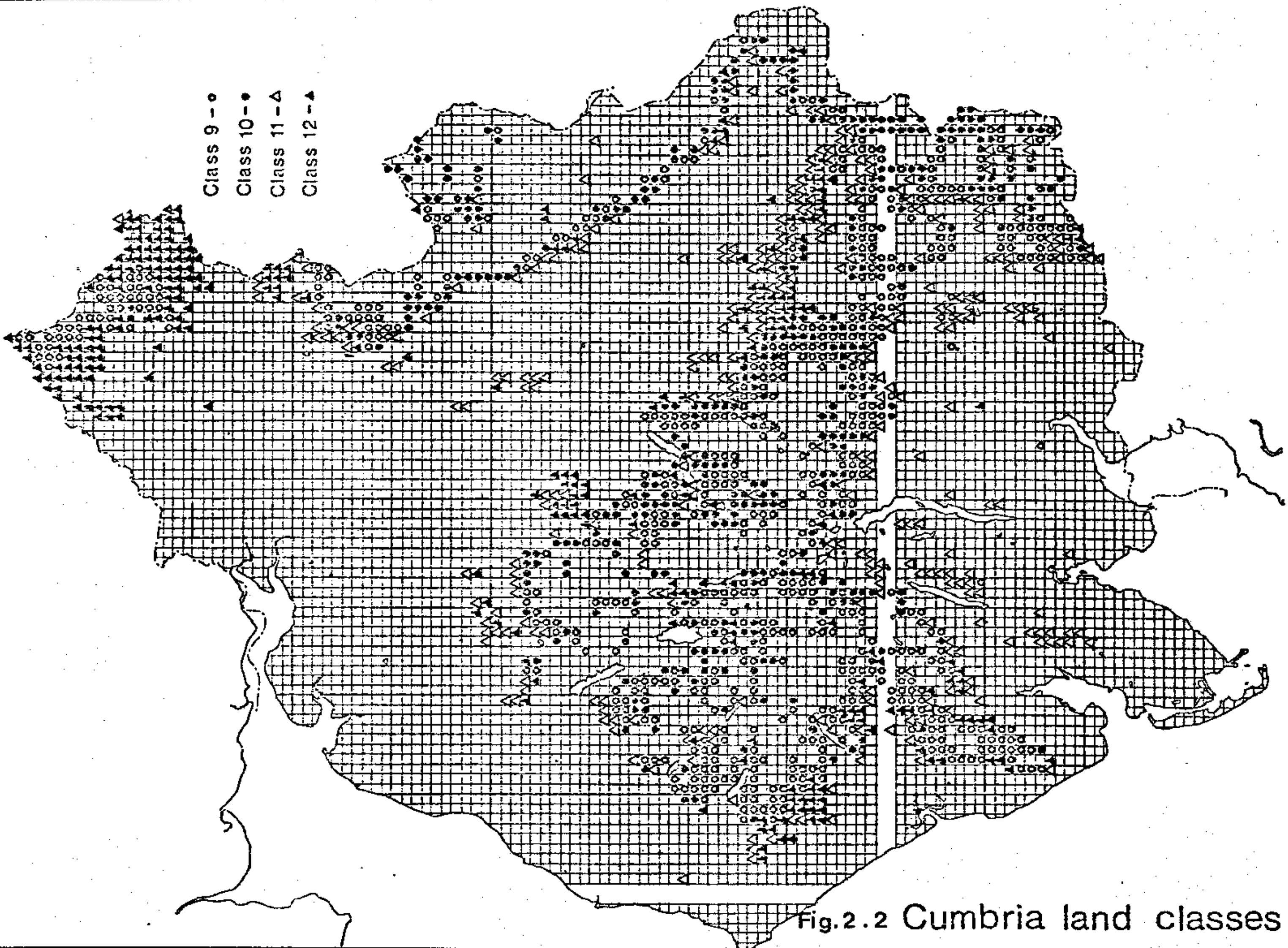


Fig. 2.2 Cumbria land classes

3. LINEAR PROGRAMMING

The name linear programming derives from the assumption that all the relationships being modelled are adequately represented by linear equations. When the variable under consideration is an area of land this assumption becomes one of twice the area twice the output, i.e. no economies of scale.

If we represent the land areas, which are our decision variables, by the set $\{x_i : x_i \geq 0\}$ then the output of some commodity, which is our objective function, is given by

$$Y = \sum_i b_i x_i$$

The objective being to maximise the value of Y. At the same time we are concerned about the output of some other commodities and wish to prescribe values below which these may not fall, these become our constraint functions. If the minimum values are (s_j) then we require

$$\sum_i a_{ij} x_i \geq s_j \qquad \text{for all } j$$

In matrix notation the linear programming problem is

$$\max Y = b^* x$$

$$\text{subject to } Ax \geq s$$

$$x \geq 0$$

where Y indicates the value of the objective function

x is a vector of decision variables
b is a vector of known coefficients
A is a matrix of known coefficients
s is a vector of known constraints.

The inequality

$$\sum a_{ij} x_i \geq s_j$$

could equally be written as the equality

$$\sum_i a_{ij} x_i = s_j + y_j \text{ where } y_j \geq 0$$

The variable y_j is known as a surplus variable. If the s_k is a maximum rather than a minimum value (which is possible under the earlier formulation by use of negatives) then we can write

$$_i a_{ik} x_i + y_k = s_k \text{ where } y_k \geq 0$$

and y_k is called a slack variable.

If commodity 'j' is produced in excess of the constraining value then the surplus variable y_j will be non-zero. If not all the land in land class k is used for some purpose then slack variable y_k will be non-zero. (This will only occur if some commodity such as energy input is being minimised).

This linear programming problem called the primal LP problem, was solved for this work using the two-phase simplex method (dèscribed by, amongst others, Van de Payne (1975) pp 60-99).

It can be shown (e.g. Trustrum, 1971 pp 19-21) that the optimal solution vector of the primal LP is the same as the optimal vector of its dual LP provided both are feasible and have optimal vectors. The dual LP can be represented as

$$\min P = s'q$$

$$\text{subject to } A'q \leqslant -b$$
$$q \geqslant 0$$

where q is the vector of decision variables and A, s and b are as defined in the primal LP.

The dual variables $\{q_i \mid q_i \geqslant 0\}$ indicate the marginal change in the level of the primal objective function resulting from a marginal relaxation in one of the constraints, or

$$q_i = \frac{\partial Y}{\partial s_i} \quad \text{(where } s_i \text{ is the ith element of vector s).}$$

A zero dual variable q_i indicates that a marginal relaxation in s_i will not affect the value of the primal objective function, as the ith constraint is ineffective. This also means that the surplus or slack variable is non-zero or basic.

A variable is referred to as basic if it is defined in the solution vector (normally with a non-zero value.)

These terms may become clearer in the context of the Cumbrian linear programming problem. Here the decision variables are the areas of land in each class given to each use. The slack variables are the unused area of any land class - land which would detract from the objective function under any of the defined land uses in that class. There is one slack variable for each land class. The surplus variables are the degree to which the output constraints are exceeded - e.g. if the surplus variable for timber production is zero then timber production has equalled, not exceeded, the constraint. There is one surplus variable for each constrained output level.

When a land use is defined for a land class in the LP solution then the corresponding decision vector is said to be in the optimal basis or, more simply, basic. Similarly, when a slack or surplus variable is non-zero it is said to be basic. Thus if the solution involves the use of some or all of land class 1 for dairy cattle then that decision variable is basic, if milk production exceeds the constraint value then a unit change in the constraint value will not affect the value of the objective function.

Some of these terms are used again in discussion of the sensitivity of results to changes in various parameters (Chap. 6).

4. INPUT AND OUTPUT COEFFICIENTS

4.1 PRESENT MANAGEMENT

Problems arise in estimating the inputs to and outputs from the land classes because although they are not strictly homogeneous, they must be treated as such for modelling purposes. The inhomogeneity can be seen in the variation in Agricultural Grade (Table 2.4) and Vegetation Group (Bunce and Smith, 1978) (Table 4.1).

The consideration of these alternate classifications of the land in the county prompts the thought that the modelling might be best pursued on the basis of one of these classifications rather than that of land class. This would certainly be tempting if our interest was restricted to agricultural productivity but as we have also determined to include in the model forestry, recreation and nature conservation, the more broadly based land classification is appropriate.

The close similarity in agricultural grade and vegetation group distributions suggests that these are derived from inherent differences in the land rather than in its treatment.* Clearly there will be changes from time to time in the extent of cultivation or pasture improvement depending on the profitability of the different farming procedures, on available capital and on the experience of the individual farmers.

But it can only be assumed, in deriving factor coefficients, that the same intensity of effort is being expended on achieving production in all parts of each individual land class. There may be differences in the approach to full realisation of potential productivity between classes (particularly between lowland and upland) and there may be changes with time (e.g. increases in agricultural productivity with changing technology and the effects of accumulating capital investment), but in each land class it must be assumed that the degree to which the land is realising its potential is the same throughout. In the first instance this level of productivity is taken to be roughly that of today's relationship of inputs and outputs.

*The variation in land quality within a land class can be seen from the few parishes which are wholly (>95%) in land class 1. The livestock carrying (GLU) ratings are derived by means described in section (4.1.2).

Parish	Composition by agricultural land Class	GLU rating
34 Holme Low	3 - 90%, 4 - 10%	185
203 Winscales	3 - 30%, 4 - 70%	140
347 Hincaster	3 -100%,	176
365 Sedgwick	3 -100%,	175
367 Stainton	3 - 50%, 4 - 50%	175
643 Mansriggs	3 - 20%, 4 - 80%	152
653 Urswick	3 - 80%, 4 - 10%, 5 - 10%	159

4.1.1 INPUTS - LABOUR and ENERGY

The input levels necessary to allow production of a particular quantity of output can be defined in terms of the output level and of the area of land from which it comes.

For example, the land being grazed by beef cattle requires a defineable quantity of labour and energy for its maintenance. At the same time each animal (or each grazing livestock unit - GLU) has its own requirements.

In attempting to give values to these requirements it is necessary to make certain assumptions and generalisations about the way the land is treated. As shown in Table 4.1 the land classes are not homogeneous but as argued above it must be assumed that this is an inherent heterogeneity and that the level of investment in the land is, throughout each land class, typical of current agricultural or forestry practice as permitted by the quality of the land.

Agriculture - Cropping

A large number of different crops are grown in Cumbria - wheat, barley, oats, potatoes, kale, oil seed rape, and various horticultural products. The majority of the produce is consumed as stock feed. The area devoted to crops for direct human consumption is only about 50-100 km^2 out of a total cropped area of about 360 km^2. The actual area of crops which is not for stock is very variable and even in the classification "Potatoes and other crops" the area dropped from 107 km^2 in 1961 to 58 km^2 in 1974 (Northern Region Strategy Team, 1976). In addition in 1974 there were 13 km^2 under wheat while a small proportion of the barley and oats crops would be for other than stock feed. Horticulture only used 1.2 km^2 of land in 1974.

Thus to define values of input requirement for cropping in Cumbria consideration was restricted to wheat (for bread making) and potatoes. The energy figures are from Leach (1976) and labour from Nix (1976). The breakdown and full derivation is given in Appendix 2.

For spring wheat, the gross energy requirement in fertiliser, fieldwork and sprays is reckoned at 1.4 TJ per km^2; the labour force required for pre-harvest preparation and collection of straw is about 150 SMD (Standard Man Days) per km^2. Input requirement for barley and oats is very similar while in each case additional labour and energy is required for storage, processing, and distribution before consumption. When the wheat is used for bread the additional energy requirement is 1.6 TJ per TJ food energy. As the labour required for baking, distribution and sales is essentially city based (i.e. not contributing to rural employment prospects) this is not included in the model and the additional rural labour component is reckoned as 30 SMD per TJ food energy output.

Similarly for potatoes the area dependent quantities are 2.6 TJ per km^2 and 470 SMD per km^2; and the output dependent are 0.019 TJ per TJ food energy (low processing requirements) and 450 SMD per TJ (high labour use in picking and riddling).

The formulae used therefore in calculating inputs to cropping products were for bread......

$$\text{Energy input} = 1.6\ \text{TJ.TJ}^{-1} + 1.4\ \text{TJ.km}^{-2}$$
$$\text{Labour} = 30\ \text{SMD.TJ}^{-1} + 150\ \text{SMD.km}^{-2}$$

and for potatoes.....

$$\text{Energy input} = 0.19\ \text{TJ.TJ}^{-1} + 2.6\ \text{TJ.km}^{-2}$$
$$\text{Labour} = 450\ \text{SMD.TJ}^{-1} + 470\ \text{SMD.km}^{-2}$$

Agriculture - livestock

Although the majority of cropped land in Cumbria is producing for livestock consumption this is only a small proportion of the total area being used primarily for livestock support. The total area of arable land in the county in 1974 was about 350 km^2. The survey of vegetation distribution (Bunce and Smith, 1978), gives estimates of the areas of different livestock support types as different vegetation groups. Although discrepancies from known figures of arable and forested land are quite large, the distribution of livestock supporting land in the county may be considered as cultivated (1500 km^2), improved pasture (1100 km^2), permanent pasture (700 km^2) and rough grazing (2600 km^2): these estimates of area reflect the vegetation survey data, the known areas of crops and forestry, and the total area of agricultural land, given by the sum of the MAFF census area and the area of common land, of about 5900 km^2.

In order to determine the energy and labour inputs to livestock support in each land class the distribution of these vegetation groups through the land classes (Table 4.1) can be used. It remains then to define the inputs to the vegetation groups.

Leach (1976) gives the gross energy consumption of certain land tending activities while similar figures for labour are available from Nix (1976). Appendix 1 gives the derivation of the total requirements as shown in Table 4.2. The energy and labour requirement per km^2 of each land class derived in this way is given in Table 4.3.

In addition, there are input levels associated with each animal. Leach (1976) gives the energy figures for cattle but only whole farm averages for sheep. Nix (1976) gives detailed labour figures for many kinds of livestock. The derivation of inputs per Grazing Livestock Unit (GLU) is given in Appendix 1 and summarised in Table 4.4.

Timber

Smith and Johnson (1977) report the energy budget of a possible intensive silvicultural programme of energy production. They estimate that for "mechanical site preparation, planting, some subsequent corrective measures, and perhaps the application of 100 pounds of nitrogen as urea during a 30 year rotation" the energy cost would be about 650 litre per hectare of fuel oil equivalent. They divide this into 470 litre for fertiliser and 180 litre for site preparation per hectare. Leach (1976) rates fuel oil at 46.6 MJ litre^{-1} so the gross energy requirements in this case are 2.2 TJ km^{-2} for fertiliser and 0.84 TJ km^{-2} for site preparation.

The UK Forestry Commission have a standard rate of fertiliser application where necessary; for example in the North West England Conservancy peaty ironpans are treated with phosphorus in years 0 and 10 of the cycle. The rates are given in Table 4.5. The energy costs of the fertilisers as given by Leach (1976) are -

Phosphorus 14 MJ kg^{-1}; Nitrogen 80 MJ kg^{-1} and Potassium 9 MJ kg^{-1}.

Thus the phosphorus treatment represents a total energy input of 0.15 TJ km^{-2} over the usual fifty year cycle.

In the example of Smith and Johnson the 100 pounds (45 kg) of urea per acre represents an energy input of 0.8 TJ km^{-2} and so the remainder of their estimate must arise from the energy cost of transporting and spreading the fertiliser.

Overall, the total energy requirement of site preparation and management should be from 1-2 TJ km^{-2} over a fifty year cycle in the UK, depending on the need for fertiliser. This is 0.02-0.04 TJ km^{-2} yr^{-1}.

Smith and Johnson quote the American Pulpwood Association's estimate of 5.16 gallons (fuel oil equivalent) per cord for harvesting - this is 0.25 GJ m^{-3}. This figure is likely to vary substantially from place to place and with species and forest management policy. It is probable that this figure includes some transportation which may be a significant cost. (In fact, for each km of transport the energy requirement is around 1.0 MJ m^{-3} - see Table 6.1).

Since the timber must be milled before any commonplace use, the energy used for milling is included in the timber production requirement. Zerbe (1971) quotes the US average figure of 0.539 kwh per board foot. This is 0.822 GJ m^{-3}. The energy cost of milling will depend on the density of the wood although to what degree is uncertain. The density of green Sitka spruce (80% moisture) is 0.58 g cm^{-3} and of beech 0.96 g cm^{-3}. On the basis of these differences and the likely split between softwoods and hardwood in the US average figure, values of 0.75 GJ m^{-3} and 1.00 GJ m^{-3} were adopted for softwood and hardwood respectively.

In an internal note the Forestry Commission estimated that in 1973-74 the total energy 'used on activities in Forestry Commission forests' was 1090 TJ (A. J. Grayson, pers. comm). This is around 0.15 TJ km^{-2} but since the plantation area is growing the proportion requiring thinning and felling is lower than for a constant area of plantation.

Figures on the labour requirements of various forestry practices are given in Table 4.6. Since concern is with rural employment the work in transport and milling is not included in further calculation. A rotation period of 60 years is assumed to convert establishment requirement to an annual figure. Road work is not included although estimates of road requirement per unit area of forest could probably be made.

The differences between FC and Private Woodland figures probably arise more from differences in scale and degree of mechanisation than from the use of different species by the two groups. Nevertheless extra labour in establishing, maintaining and logging would be required in deciduous plantations and for this exercise estimates of labour inputs to coniferous forest are made fromthe Forestry Commission figures and to deciduous forest from Private Woodland data.

A summary of the inputs to forestry is given in Table 4.7.

Table 4.1 Distribution of vegetation groups with land class

Land class	Vegetation group			
	Cultivated (1-8)	Improved pasture (9-12)	Permanent pasture (13-16)	Rough grazing (17-32)
1	25	43	12	21
2	72	13	10	6
3	21	19	54	6
4	14	36	4	41
5	75	12	3	10
6	63	30	5	3
8 *	55	41	4	-
9	-	-	-	100
10	2	23	15	60
11	-	10	23	67
12	9	9	28	54
13	-	-	-	100
14	-	-	-	100
15	-	-	3	97
16	-	-	-	100

* A large part of the total area in class 8 squares is beach or mud or sea. These figures represent proportions of the remaining vegetated area.

Table 4.2 Labour and energy inputs to vegetation by groups

Vegetation group	Energy (TJ km^{-2})	Labour (SMD km^{-2})
Arable	1.56	286
Leys	1.27	245
Improved pasture	1.09	59
Permanent pasture	0.77	51
Rough grazing	-	-

Table 4.3 Labour and energy inputs to agricultural land by land class

Land class	Energy (TJ km^{-2})	Labour (SMD km^{-2})
1	0.88	93
2	1.18	195
3	0.88	90
4	0.60	58
5	1.22	209
6	1.19	179
8*	1.23	169
9	-	-
10	0.39	26
11	0.28	18
12	0.43	42
13	-	-
14	-	-
15	0.02	2
16	-	-

*Based on the 73% of class 8 assigned to vegetation groups

Table 4.4 Labour and energy inputs per unit of Livestock (from Appendix 2)

	Energy (TJ GLU^{-1})	Labour (SMD GLU^{-1})
Dairy	0.0124	5.7
Beef	0.0087	3.2
Sheep - lowland	0.0044	2.4
- upland	0.0059	3.3
- hill and fell	0.0077	4.1

Table 4.5 Rate of Fertiliser Application - UK Forestry Commission (F.C. pers. Comm.)

Element	Form	Rate (kg ha^{-1})	Active percentage	Rate (kg ha^{-1})
P	rock phosphate	375	11-17	~53
K	muriate of potash (KCl)	200	50	100
N	prilled urea	375	46	173

Table 4.6 Labour requirements for various forestry practices (A. J. Grayson, Forestry Commission, pers. comm.)

Operation	Unit	F.C.	Private
Establishment	man-year ha^{-1}	0.072	New planting 0.09 Restocking 0.11
Forest protection and maintenance, road maintenance	man ha^{-1}	0.0021	0.0040
Road construction including reconstruction	man-year km^{-1}	2.42	3.5
Logging	man-year m^{-3} O.B.	0.00175	0.0021
Transport and milling	man-year m^{-3} O.B.		
- small roundwood		0.0025	
- sawlogs		0.0037	

O.B. - measured over bark

Table 4.7 Labour and energy inputs to timber production

	Energy (TJ)		Labour (SMD)	
	per km^2	per 100 m^3	per km^2	per 100 m^3
Softwoods	0.02-0.04*	1.00	83	440
Hardwoods	0.02-0.04*	1.25	130	530

*Depending on fertiliser requirement as given in Table 11.

4.1.2 OUTPUTS - TIMBER, AGRICULTURAL PRODUCTS

Timber

The potential production of timber from a forest is commonly designated as the Yield Class (Y.C.). The Y.C. figure is an estimate of the output of timber in cubic metres per hectare per annum ($m^3 ha^{-1} yr^{-1}$) and depends on

i) the species
ii) management practice
iii) soil condition including wetness
iv) climate, particularly temperature and exposure

Busby (1974) has summarised the yield classes under a variety of combinations of these factors. Table 4.8 gives his results for the Forestry Commission's (FC) North West England Conservancy.

Assessing the potential for timber production from the Cumbrian land classes therefore requires knowledge of the soil condition of each land class. Unfortunately, the largest scale soil map covering the county is the 1:1 000 000 "Soil Map of England and Wales". The soil categories used do not coincide with those of Busby and the scale of the map is such that a reliable estimate of soil condition in any kilometre square is not possible. However, this was attempted, in the knowledge that adjustments could be made on the basis of local experience.

The soil types given on the map as occuring in Cumbria are listed in Table 4.9. The distribution of these between the land classes was then estimated by determining the soil type in each of eight random squares in the 16 land classes. Where the scale of the map made this uncertain the two or three possible soil types for the square were considered to cover one half or one third of it. On this basis the distribution given in Table 4.9 were obtained.

Softwoods

To assign yield class values to the soil types defined from the map the values given by Busby were used as a basis. The best of the mapped soil grades (Type 62) was given the highest yield class listed by Busby with other grades being matched to or compared with Busby's soil groups where possible. The variation with altitude also followed Busby although it was felt necessary to introduce further divisions at 450 m, 525 m and 600 m altitude. Estimates of yields at these greater heights were made from other sources......

There is evidence from the North Pennines of the growth rates of Norway spruce and Sitka spruce above 450 m. Millar (1964) wrote "Given shelter from wind, tree growth is possible up to 2000 ft. at least. Under the topographical conditions of Alston Moor this is likely to apply only to occasional trees growing, for example, in small hillside clefts. If the forest limit is defined as the zone where forest gives way to open moor, then it probably lies between 1800 and 1900 ft. at its highest."

White (pers. comm.) reported observations of Norway spruce at Ashgill (NY770400) in 1962. He gives evidence of a yield class of 6 at 490 m, but less than 4 at 525 m on thin peat. More recent Sitka Spruce plantations in the same area are not yet of sufficient size to indicate a yield class. Williams (1975) suggests that 10 would be optimistic and the local Forestry Commission Officer expects a yield class of 6-8 at 490 m on peaty gley or surface water gley despite some checking with heather (pers. comm.).

The values of yeild class by soil type and altitude (Table 4.10) were combined with the distribution of soils by land class (Table 4.9), and the predominant altitudes of the land classes (Tables 4.9 and 4.11). The results are in the second column of Table 4.12.

Visits were made to the Forestry Commission's Grizedale and Dunnerdale forests to gain empirical evidence of growth rates in the different land classes. There was sufficient use of land classes 1, 2, 4, 9 and 11 under both Sitka spruce and Japanese larch to assess the yield class of these species. Forest compartments which fell wholly within squares of one land class were selected from different parts of the forest and the mean values are given in second and third columns of Table 4.12. It can be seen that these vary in a similar way to the theeretical values. That they are generally lower reflects Forestry Commission policy to make their own estimates of yield class conservative. The only important departure from the pattern of the theoretical values is the low result from the forests of land class 4. Although this class generally lies in the lowest of the altitude ranges given by Busby, it does lie in the upper part of this range: this, and the likelihood of greater exposure in this class support the evidence of the empirical score which is nearer to that of class 11 than class 1. The mean Y.C. for class 4 was accordingly changed to 13.0.

In calculating the annual yield of the land classes the Forestry Commission practice of allowing 15% of forest area for roads and rides was followed. That is the yield class is multiplied by 85 to get productivity in $m^3 km^{-2} yr^{-1}$ (Table 4.12).

Hardwoods

Timber production from deciduous woodland is generally lower than that of the coniferous forest although a yield class of 14 has been reported in England for the South American genus *Nothofagus* (Southern beech). Among native species yield classes up to 8 occur under beech and slightly less under oak. The Forestry Commission assigns a nominal yield class of 4 to its broadleaved plantations.

In assessing the likely yields of the Cumbrian land classes a yield class of 6 was given to class 2 with the other lowland classes reducing in the same way as for softwoods. Above 300 m yield was taken to reduce more rapidly with altitude.

Agricultural products

Although the distribution of agricultural grades and vegetation groups by land class is established (Tables 2.4, 4.1) the actual productivity of the individual grades or groups has not been defined in any way.

Some estimates were made (MAFF, pers. comm.) in 1971 to estimate the potential monetary output of the agricultural grades. Although no conclusions were drawn, and the many difficulties of the exercise discovered, some measure of the relative productivities of the grades was produced. Since then, prices, productivities and farming practice have all changed and thus the figures given in Table 4.13 are proposed only as a very rough guide to relative output.

In view of this uncertainty, empirical evidence of the productivity of the land classes was sought. Difficulties arise because agricultural Dataare collected on a parish basis. Parish boundaries naturally do not follow grid square boundaries. Nevertheless the Agricultural Census results from 1973 and other information were analysed and the stock support ability of the land classes estimated........

Stock support ratings

The demand for food varies from animal to animal but those of the same type and function are assumed to require the same quantity. Thus a dairy cow is defined as one grazing livestock unit (GLU) while a hill ewe is rated at one-tenth of a GLU. The figures for other animals are given in Table 4.14.

Although the parish returns contain livestock populations in a range of categories, these figures have not been transferred into a form suitable for computer analysis at Merlewood. Onlythe 'Total Cattle and Calves' and 'Total Sheep and Lambs' in each parish have been treated in this way.

There were 290 parishes in Cumbria in June 1973 and rather than rework all the livestock data a sample was taken to estimate the relationship between these totals and the GLU in the parish. The GLU ratings of Table 4.14 were applied to a random group of parishes to estimate the relationship between 'Total Cattle and Calves' and the total GLU, and then between the number of potential milking cows and GLU (Table 4.15 (b)). Estimates of the same ratios can also be derived from knowledge of farm management practices (Table 4.15 (a)). It can be seen that the two methods give good agreement and it can be safely suggested that GLU rating of the parish, in cattle, is given, to a good approximation, by between 0.61 and 0.69 of the 'Total Cattle and Calves' depending on the proportion of beef to dairy cattle.

A similar procedure may be followed for 'Total Sheep and Lambs' (see Table 4.16). As Table 4.14 shows, the breeds which are classified as hill sheep require considerably less food than lowland breeds, but the two are not distinguished in the Census returns. Table 4.16 implies a ratio of 0.64 between ewe equivalents and 'Total Sheep and Lambs' - where a ewe equivalent is between 0.2 GLU and 0.1 GLU depending on breed and environment.

In order to estimate the GLU rating of the parishes it is necessary to estimate which class of sheep are likely to be found there. It was assumed that the proportion of hill sheep rises rapidly with the proportion of land in classes 9 to 16. To accomodate this variation the term $(1+A^3)$ was introduced into the calculation of GLU values. If A is the proportion of the parish in land classes 1 to 8 then the effect is to give a value of 0.113 to each ewe when the parish is 50% lowland, or 0.173 GLU when 90% lowland.

Thus, the capacity of each parish was calculated as.....

$$0.64\ (C + S\ (1 + A^3)/10) \text{ where } C = \text{total cattle and calves}, \quad S = \text{total sheep and lambs}$$

Dividing by the area of agricultural land in the parish (i.e. the total area given in farmers' census returns) gives a GLU per km^2 rating for each parish. Some error has been introduced here because as the parish figures show the relationship between numbers of young stock the mature stock are not constant throughout the parishes. In some areas emphasis is on breeding and in others on fattening so that the June figures bear a different relationship to overall carrying capacity in each case. Thus even in the parishes analysed in Table 4.15 (b), variations of up to 10% of the mean ratios occurred. The values of GLU km^{-2} for the parishes cannot therefore be considered to be any better than ± 10% and possibly worse in the marginal lands where the type of sheep is in doubt. The most reliable estimates will be those in the dairy dominated parts of the lowlands. Where there is substantial common land or other special circumstances in the parish divergence will be most pronounced.

The estimated stocking densities were plotted against the percentage of one or more classes in the parish. Thus in Fig. 4.1 which shows the GLU values against percentage of land in class 1 it can be seen that when the percentage is low the scatter is wide because the additional land in the parish may be of any quality. The points converge as the percentage approaches 100, i.e. all the parish is in land class 1. Some scatter is still evident reflecting the error in the GLU estimates, different intensities of labour or energy investment to the land, or other factors having local effects on farming efficiency. The plots for classes 2-5 are shown in Figs. 4.2-4.5.

The stocking rate in any parish (remembering the influence on the figures of common land) gives a minimum estimate of the carrying capacity. The potential stocking rate (or carrying capacity) is taken to be the best being achieved with some consistency in each land class. Clearly this stocking rate achieved will also depend on the applied technology, methods of husbandry, and intensity of operation. In addition to local variation there is a general increase in agricultural productivity of around 2% per annum in the U.K. (C.A.S., 1976).

While stocking rates in classes 1 to 5 were estimable in this way the other land classes did not, individually, so dominate any parish that estimates could be made.

Class 7 is largely mud and sand and was excluded from the model. The plot for class 8 and the distribution of agricultural grades within it suggest marked similarity to class 1. Similarly, class 6 is very much like class 5, possibly having a slightly higher agricultural productivity.

Estimates for the hills and fells can be derived from consideration of figures for the Hartsop Valley in central lakeland. Feist et al (1976) gives the total livestock population of the valley as (in June) 9000 sheep and lambs, 211 suckler cows, 6 bulls and 236 young stock (calves reared to stores and for a cow replacement). This stocking represents a year round carrying of about 800-850 GLU.

Grazing land in the valley is categorised as 1.8 km^2 in-bye, 2.0 km^2 allotment, 20 km^2 enclosed high fell, and 10.5 km^2 common high fell. In terms of land class the division is.....

Land class	Area (km^2)
9	5.8
10	8.6
11	1.0
14	1.0
15	2.5
16	15.4
	34.3

Clearly the land classed as high fell does not all fall in land classes 14-16, but also includes all of 9 and a large part of 10. The carrying capacity of the valley as a whole is 24 GLU km^{-2} (for 823 GLU total).

In using this figure to estimate stocking rates for individual land classes, the following points are relevant.....

i) in reckoning stocking capacities it is conventional (in M.A.F.F. publications for example) to take 3 units of rough grazing land as equivalent to 1 unit of in-bye. While both types are clearly of variable quality this might be taken as a fair comparison of land classes 11 and 15;

ii) a hill stocking rate of 2.5 acre per ewe (15 GLU km^{-2}) is common and reasonable (M.A.F.F., pers. comm.);

iii) the distribution of Agricultural grades (Table 4.21) indicates that class 11 is the best of the upland classes followed by 12, 10 and 9; and

iv) classes 13 and 14 have a slightly cooler climate and a more acid soil (Table 4.41) and will have lower potential stocking rates than classes 15 and 16 respectively.

Although the extension of current stocking in the Hartsop Valley to the whole county is an unreliable method there are no other data available now. The uncertainty is particularly high in land classes 9 to 12. It was on these bases that the stocking rates given in Table 4.25 were chosen.

As a check on these values they were used to predict the stocking rate of each parish and these values were plotted against the parish ratings derived from the census data. Figure 4.6 shows a large scatter about the equality line.

Checking those parishes in which the predicted value was more than 35% higher or lower than the census rating (Fig. 4.7) revealed that parishes in which the actual value exceeded the predicted value by this amount were those containing large areas of common land. Where the actual quantity of stock in the parish was less than expected, a number of explanations seem to apply. In some areas, for example parts of the North Pennines, the land is not being used to capacity. In others, such as Langdale, the pressures of recreation and the devotion of farmers' time to catering for tourists may lessen stocking. It may be that while the parish itself contains quite good land flocks or herds are being grazed on inferior land in another parish. Some parishes contain large areas classified by the farmers as rough grazing although the land class is entirely lowland - this may be poorly drained peat marsh or land subject to innundation.

The values of GLU km^{-2} assigned to the land classes (Table 4.17) are thought to be a fair reflection of the potential of most of the land in each class, i.e. the stocking capacity with present management techniques and the investment of labour and energy as defined.

Conversion of grazing potential to output

Having determined a measure of the livestock carrying capacity of each land class it remains to convert these figures into output values of milk, meat, food energy and wool.

In Cumbria a stock animal will often move from one land class to another during its life time. For example, lambs born to hill ewes are generally sold at an early age and fattened on richer lowland pastures. This system of management creates difficulties in translating carrying capacity into food output.

One might consider that the contribution of the land is measured by the level of edible product created during the stay of each animal in each land class. Thus, for example, if each hill ewe produces one lamb each year which is sold with a live weight of 10 kg then the meat production per ewe is approximately 5 kg (carcass weight being approximately 50% of live weight at time of slaughter). Then, if the lambs are sold after fattening at a live weight of 50 kg then the latter land class has added 20 kg to the carcass weight.

However, it is clear that land which supports breeding stock will produce less food per livestock unit (whatever the land class) than land devoted purely to fattening. Nevertheless, some land must be used for breeding, and so the hill land which is unsuitable for fattening in fact contributes more to county food production than simply the weight of lambs sold each year. If the breeding were not done on the hills it would be necessary to use land elsewhere for this purpose. Therefore in calculating the output from different land classes, the food production per livestock unit was taken to vary only with environmentally induced changes in fertility, mortality, weight gain or milk production rates and not with different management practices.

a) Dairy cattle ...

Table 4.15 (a) indicated that one GLU km^{-2} means 0.60 milking dairy cows per km^2. Leach (1976) gives an average U.K. production of 4.14 tonnes of milk per Fresian - year. Local figures (A.D.A.S., 1976) give figures of 4.73 tonnes for lowland herds and 4.01 tonnes for upland (150-300m) dairying. This is equivalent to 2.55 and 2.17 tonnes per GLU.

Meat production depends on calving rates, the weight of calves at selling age and of culled cows, the culling rate and the ratio of live weight to dressed carcass weight. Table 4.18 gives the values used; these give a productivity of 126 kg per GLU in the lowlands and 113 kg per GLU on higher ground.

Conversions to food energy are 2.72 MJ kg^{-1} for milk and 10.17 MJ kg^{-1} for beef (Leach, 1976).

(b) Beef cattle ...

For beef cattle one GLU means 0.68 beef cows. Carving rate reduces at higher altitudes and meat production drops from 147 kg GLU^{-1} to 119 kg GLU^{-1}.

(c) Sheep ...

The range both of demand for food and of lambing rate between lowland and the hills is considerably greater in sheep than cattle. Different breeds are chosen for different conditions.

In the lowlands a ewe is reckoned as 0.2 GLU and the expected lambing rate is 130% (see Table 4 (b)). This means that one GLU represents 3.64 ewes, and with a 25% cull rate and 5% ewe mortality, annual sales are 3.64 lambs per GLU and 0.91 cull ewes. Taking the respective carcass weights of these animals as 20 kg and 27 kg, meat production is 97 kg/GLU.

On higher slopes (e.g. land class 9-12) lambing rate has declined to 110% and a ewe is reckoned as 0.12 GLU. Lambs are generally sold as stores and fattened to 90% of the weight of the lowland lamb with ewes at half lowland weight. Under these assumptions one GLU represents 5.0 hill ewe, and annual sales are 4.02 lambs and 1.26 cull ewes. This is 92 kg meat per GLU.

The conditions of hill and fell reduce lamb survival rate to 75% which makes one GLU the equivalent of 6.33 ewes. Annual sales are thus 2.85 lambs and 1.68 cull ewes and meat production (lambs achieving 80% of lowland weight) is 68 kg per GLU.

The food energy conversion for lamb is 12.81 MJkg^{-1} so energy production in the three situations is 1.26GJ.GLU^{-1}, 1.18 GJ.GLU^{-1} and 0.88GJ.GLU^{-1}.

Weight of fleece in lowland, upland and hill and fell is estimated as 3.2 kg, 2.3 kg and 1.6 kg respectively. This is 11.6 kg GLU^{-1}, 11.6 kg GLU^{-1} and 10.3 kg GLU^{-1}.

Table 4.19 summarises the livestock productivities.

Land class productivities

The output of animal products from each land class can now be readily determined from Tables 4.17 and 4.19. Tables 4.36, 4.37 and 4.40 give the resulting figures.

Productivity under cropping cannot be checked from any known data and the estimates given in Table 4.13 for the agricultural grades must be extended to the land classes. As a check on this procedure the ratios produced in this way for dairying were compared with the ratios of the dairy figure in Table 4.40. This is not a wholly valid comparison since the figures in Table 4.40 represent the entire produce of dairy cattle while the estimates for the agricultural grades assume specialist dairy farming with calves sold early. The drop in productivity with reducing land quality would therefore be expected to be higher in the latter case. Table 4.20 shows the comparison.

In Table 4.21 are the ratio for cereal and horticulture calculated in the same way (taking cereal productivities as equivalent to the 'mixed arable' category of Table 4.13). It can be seen that because the productivity of horticulture drops more rapidly with deteriorating land quality than cereal productivity the former is unlikely to be considered outside land classes 2, 5 or 6. Unfortunately there are no estimates of potato growth by land class. Nevertheless, in estimating outputs by land class potatoes were taken as the crop in classes 2, 5 and 6 while wheat was taken to be the most likely crop in classes 1, 3, 4 and 8.

Leach (1976) gives the average UK outputs as wheat (as bread) 4.4 TJ km^{-2} and potatoes 5.7 TJ km^{-2} (compared with sugar (from beet) 8.3, carrots 3.0, peas 1.0). If these are taken as the productivities of land class 6 then those of the other classes follow from the ratios of Table 4.21.

Table 4.8 Site yield guides for the Forestry Commission North West England Conservancy (from Busby, 1974)

Soil group		Brown earths		Podsols Intergrades Weak ironpans		Peaty ironpans		Surface water gleys	Peaty gleys Flushed peats		Unflushed peats		Brown earths		
Factor affecting choice of species		Moist	Dry	Moist	Dry	Moist	Dry	-	Flush	Unfl.	Slopes	-	Minor species		
Main species		SS	CP	SS	CP	SS	LP	SS	SS	LP	SS	LP	HL	DF	Bl/ Con
Chemical regime: (application necessary to achieve predicted yield class)	Year 0					P	P	P	P	P	P	P			
	10					P	P	-	P	P	PK	P			
Elevation zone Lower 0-225 m	Yield class	16	12	13	11	12	11	15	12	10	13	10	10	15	6
	Terminal height (m)	-	-	-	-	-	-	21	21	21	21	21	-	-	-
	Rotation (to nearest 5 yr)	50	50	55	50	55	50	40	50	50	45	50	45	45	150
Mid 225-375 m	Yield class	14	-	11	9	10	9	13	10	8	11	8	-	-	-
	Terminal height (m)	-		-	-	21	21	19	19	19	19	19			
	Rotation (to nearest 5 yr)	55		55	50	55	50	40	50	50	50	50			
Upper >375 m	Yield class	12	-	10	7	9	7	11	9	7	10	7	-	-	-
	Terminal height (m)	-		-	-	18	18	16	16	16	16	16			
	Rotation (to nearest 5 yr)	55		55	55	50	50	40	45	50	40	50			

Notes:

i) local variations of up to ± 3 m^3 per annum can be expected.

ii) the yield class values are for the mid-slope position, that is, moderately exposed.

iii) the yield classes are dependent on the use of phosphorus (P) and potassium (K) fertilisers as indicated.

iv) species given are -

Bl - Broadleaved species

Con - Conifer species

CP - Corsican pine, _Pinus nigra_ var. _maritima_

DF - Douglas fir, _Pseudotsuga menziesii_

HL - Hybrid larch, _Larix x eurolepis_

LP - Lodgepole pine, _Pinus contorta_

SS - Sitka spruce, _Picea sitchensis_

Table 4.9 Soil types from the "Soil Map of England and Wales", Director General of Ordnance Survey, Southampton

Soil type	Dominant soil group	Associated soil groups
1	Raw sands	Raw skeletal soils and sandy gley soils
5	Alluvial gley soils	Brown alluvial soils
9	Earthy peat soils	Humic gley and sandy or humic - sandy gley soils
55	Stagnogley soils	Argillic brown earths or brown earths
60	Brown earths	Rankers or rendzinas and bare rock (limestone pavement)
62	Brown earths	Podzols and brown sands
63	Brown earths	Stagnogley soils and brown podzolic soils
66	Stagnopodzols	Stagnohumic or humic gley soils, brown podzolic soils, rankers and peat soils
67	Stagnopodzols	Rankers, raw skeletal soils, stagnohumic gley soils, or bare rock
69	Stagnogley soils	Brown earths or argillic brown earths, brown podzolic soils and stagnohumic gley soils.
70	Stagnohumic gley soils	Peat soils, humic gley soils and stagnopodzols
71	Raw peat soils	Stagnohumic or humic gley soils, earthy peat soils and stagnopodzols.

Table 4.9 (Cont.) Distribution of soil types by land classes

Land class	Soil type 1	5	9	55	60	62	63	66	67	69	70	71	Altitude (metres)
1		0.19					0.44	0.31			0.06		75-150
2						0.44				0.56			75-150
3					0.25					0.75			225-300
4						0.25	0.25	0.12		0.25	0.13		150-225
5				0.19		0.13	0.19	0.13		0.36			0-75
6		0.13		0.06		0.13	0.06			0.62			0-75
7	0.63	0.25	0.06							0.06			0-75
8	0.13	0.25		0.06			0.06			0.50			0-75
9							0.12	0.06	0.58		0.20	0.06	300-350
10							0.25	0.12	0.45		0.06	0.12	300-450
11		0.06					0.30	0.25	0.13	0.13	0.13		225-300
12							0.06	0.31	0.13	0.25	0.13		225-300
13									0.06	0.25	0.31	0.38	450-600
14								.06	.06		0.44	.44	525 +
15							0.38	0.25	0.13	0.12	0.12		375-600
16							0.12	0.25	0.63				450 +

Note: The land classes do not necessarily fall entirely within the altitude ranges given. The range indicates the most likely altitudes of points within the land class.

Table 4.10 Yield classes by soil type and altitude (for suitable softwood species).
(No estimate is given where not required in the Cumbrian situation)

Altitude (metres)	Soil type 1	5	9	55	60	62	63	66	67	69	70	71
0-225	11	15	15	15	14	16	15	13	-	15	12	-
225-375	-	13	-	-	12	-	13	11	9	13	10	11
375-450	-	-	-	-	-	-	11	10	8	11	9	10
450-525	-	-	-	-	-	-	9	8	6	9	7	8
525-600	-	-	-	-	-	-	3	3	2	3	2	3
600 +	-	-	-	-	-	-	0	0	0	0	0	0

Table 4.11 Altitudinal distribution of land classes 13-16 as used for calculated yield classes

Land Class	Percentage	Range (metres)
13	60%	450 - 525
	40%	525 - 600
14	40%	525 - 600
	60%	600 +
15	40%	375 - 450
	40%	450 - 525
	20%	525 - 600
16	20%	450 - 525
	40%	525 - 600
	40%	600 +

Table 4.12 Estimates of yield class by land class

Land class	From soils SS	From forest data SS	From forest data JL	Imputed hardwoods	Production ($m^3km^{-2}yr^{-1}$) Softwood	Production ($m^3km^{-2}yr^{-1}$) Hardwood
1	14.5	12.6	11.7	5.6	1230	480
2	15.4	14.0	12.0	6.0	1310	510
3	12.8			5.0	1090	430
4	14.6	11.0	9.0	5.1	1110	430
5	14.9			5.8	1270	490
6	15.1			5.9	1280	500
7	12.6			4.9	1070	420
8	14.5			5.6	1230	480
9	9.4	8.1	9.0	3.0	800	260
10	9.9			3.2	840	270
11	11.6	10.2	9.0	4.5	990	380
12	11.3			4.4	960	370
13	5.7			1.0	490	85
14	1.0			0	85	0
15	6.6			1.5	560	127
16	2.3			0	200	0

Notes:

i) the yield class used in calculating production for land class 4 was 13.0

ii) production = 85 x yield class

iii) SS - Sitka spruce (<u>Picea sitchensis</u>)
JL - Japanese larch (<u>Larix kaempferi</u>)

Table 4.13 Relative productivities of agricultural grades under different uses.
(Based on preliminary monetary assessments by M.A.F.F., pers. comm.)

Agricultural grade	Mixed arable	Dairy	Horticulture
2	20	23	110
3	14	16	35
4	8	10	8
5	1	1	1

Note: The figures on which these are based were of profitability and therefore relate to both input and output levels whereas they are to be used here as measures of relative output only.

Table 4.14 Grazing livestock units (from Nix, 1976)

Dairy cows	1.0
Beef cows (excluding calf) and other cattle over 2 years old	0.8
Semi-intensive beef (6 to 15-18 months old)	0.7
Other cattle 1 to 2 years old	0.6
Other cattle under 1 year old	0.4
Lowland ewes (including lambs under 6 months old), Rams and Tegs (over 6 months old)	0.2
Hill ewes	0.1

Table 4.15(a) Analysis of cattle herd composition - some assumptions

Calving rate	0.89 live calves per cow per year
Herd life	6 years i.e. culling rate 0.17 cows per cow per year
Age of calf sale	18 months

Then if the number of dairy cows is y

	Total cattle and calves	GLU Dairy	GLU Beef
Cows	y	y	0.8y
Calves 1 year	0.89y	0.36y	0.45y
Calves 1-2 year			
- for herd	0.17y	0.10y	0.10y
- for sale	0.36y	0.22y	0.22y
Total	2.42y	1.68y	1.48y

so,

GLU/total cattle and calves = 0.69 Dairy
or 0.61 Beef

Milking cows/GLU = 0.60 Dairy
or 0.68 Beef

With a drop in live calving rate for hill beef to 0.87 the ratios are unchanged.

Table 4.15 (b) Analysis of cattle herd composition - some Cumbrian parishes

Parish	Cows in milk		In calf		Bulls	Other cattle					
	Dairy	Beef	Dairy	Beef		2 years	1-2 years	½-1 year	6 months	GLU	*Total cattle & calves
29 All Hallows	299	28	98	10	2	15	190	126	122	597	890
34 Holme Low	1468	132	693	38	30	241	945	893	468	3377	4908
57 Millom Without	775	311	315	75	32	87	656	455	439	2213	3145
96 Cockermouth	258	186	85	8	13	53	528	198	181	870	1510
101 Gilcrux	292	118	73	92	8	76	349	310	163	818	1481
121 Farlam	416	319	93	113	55	35	265	288	329	1259	1913
125 Midgeholm/ Geltsdale	-	204	-	16	11	-	20	46	155	315	452
145 Culgarth	583	487	312	184	27	105	804	869	350	2266	3721
313 Crosby Garrett	189	8	153	7	3	23	138	135	95	495	733
316 Musgrave	546	45	216	12	15	17	290	257	150	1085	1548

Mean ratio: GLU/total cattle & calves = 0.65 sd = 0.05

Mean ratio potential dairy cows+/GLU = 0.65 sd = 0.06

*Computed using figures in Table 4.14 and assuming that the animals 1-2 years old spend only half the year in the parish (going for slaughter at age 18 months).

+Includes all dairy cows and heifers and (beef cows and heifers) x 0.8

Table 4.16(a) Analysis of flock composition - some assumptions

(i) Lowlands (land classes 1-8)

Lambing rate 1.30 lambs per ewe per year

Flock life 3.3 years i.e. culling rate 0.25 ewes per ewe per year
and ewe mortality 0.05 per ewe per year

Age of lamb sales 6 months

Ewe with lamb ($<$6 months) = 0.2 GLU

If number of ewes is y

	Total sheep and lambs	GLU
Ewes and	y	0.2y
lambs (6 months)	y	
Lambs 6 - 12 months	0.3y	0.015y
Hoggs	0.3y	0.06y
Total	2.6y	0.275y

so,

GLU/total sheep and lambs = 0.106
Ewe equivalents/total sheep and lambs = 0.53
Ewes/GLU = 3.64

(ii) Uplands (land classes 9-12)

Lambing rate 1.10 lambs per ewe per year

Ewe = 0.12 GLU

	Total sheep and lambs	GLU
Ewes	y	0.12y
Lambs sold	0.8y	0.029y
Lambs for flock	0.3y	0.022y
Hoggs	0.3y	0.029y
Total	2.4y	0.20y

so,

GLU/total sheep and lambs = 0.083
Ewe equivalents/GLU = 0.69
Ewes/GLU = 5.0

Table 4.16(a) (Cont.)

(iii) Hill and fell

Lambing rate 0.75 lambs per ewe per year

Ewe = 0.1 GLU

	Total sheep and lambs	GLU
Ewes	y	0.1y
Lambs sold	0.45y	0.016y
Lambs for flock	0.3y	0.018y
Hoggs	0.3y	0.024y
Total	2.05y	0.158y

so,

GLU/total sheep and lambs	=	0.077
Ewes equivalents/total sheep and lambs	=	0.77
Ewes/GLU	=	6.33

N.B. In all cases, the ratio of GLU to total sheep and lambs will rise if some lambs are sold before census time

Table 4.16(b) Analysis of flock composition - some Cumbrian parishes

Parish	Lambs 1 year	Total sheep and lambs	Ewe equivalents*	Ewe equivalents / Total sheep and lambs
29 Allhallows	262	426	230	0.54
34 Holme How	629	1092	620	0.57
57 Millom Without	4361	10128	6857	0.68
96 Cockermouth	1156	3715	2848	0.77
101 Gilcrux	923	1729	1037	0.60
121 Farlam	2447	5209	3374	0.65
125 Midgeholm/ Geltsdale	4717	10208	6670	0.65
145 Culgaith	5754	11964	7649	0.64
313 Crosby Garrett	1045	1978	1194	0.60
316 Musgrave	1773	3794	2464	0.65
				0.64±.06

*Assuming 75% of lambs are only 6 months in the parish, and that one lamb eats 0.4 of ewe's consumption per unit time.

Table 4.17 Land class stocking rates

Land class	1	2	3	4	5	6	8	9	10	11	12	13	14	15	16
GLU km^{-2}	170	180	155	135	190	190	170	40	75	75	75	25	10	30	12

Table 4.18 Livestock sale weights (M.A.F.F., pers. comm.)

	Live weight (kg)	Dressed carcass weight/live	Dressed carcass weight (kg)
Calves (18 months) - beef - dairy	425	0.56 (range 0.52-0.62)	238
Cull cows (6 years) - beef	500	0.51	255
Cull cows (6 years) - dairy	500	0.45	225

Table 4.19 Livestock produce per GLU

	Land classes 1-8	Land classes 9-12	Land classes 13-16
DAIRY			
Milk (tonnes)	2.83*	2.41	-
Meat (kg)	126	113	-
Food energy (GJ)	8.99*	7.71	-
BEEF			
Meat (kg)	147	132	119
Food energy (GJ)	1.50	1.34	1.21
SHEEP			
Meat (kg)	98	92	69
Food energy (GJ)	1.26	1.18	0.88
Wool (kg)	11.6	11.6	10.3

*In land classes 3 and 4 milk per GLU was taken as 2.41 tonnes and so food energy as 7.83 GJ per GLU.

Table 4.20 Comparison of relative productivities of dairy cattle as derived from (i) Tables 2.2 and 4.13, and (ii) Table 4.22 (or 4.17 and 4.19)

Land class	Productivity relative to agricultural Grade 5	Ratios (i)	Ratios (ii)
1	12.7	0.80	0.89
2	14.8	0.94	0.95
3	10.0	0.63	0.70
4	7.8	0.49	0.60
5	15.0	0.95	1.00
6	15.8	1.00	1.00
8	13.8	0.87	0.89
9	1.1	0.07	0.18
10	1.9	0.12	0.34
11	3.5	0.22	0.34
12	2.1	0.13	0.34

Table 4.21 Productivity of cropping and horticulture by land class (from Tables 2.2 and 4.13)

Land class	Crops	Horticulture
1	0.80	0.64
2	0.93	0.93
3	0.61	0.36
4	0.47	0.27
5	0.95	0.95
6	1.00	1.00
8	0.88	0.69

In relation to a score of 1 for grade 5 land the productivities in class 6 are 13.7 (crops) and 36.5 (horticulture).

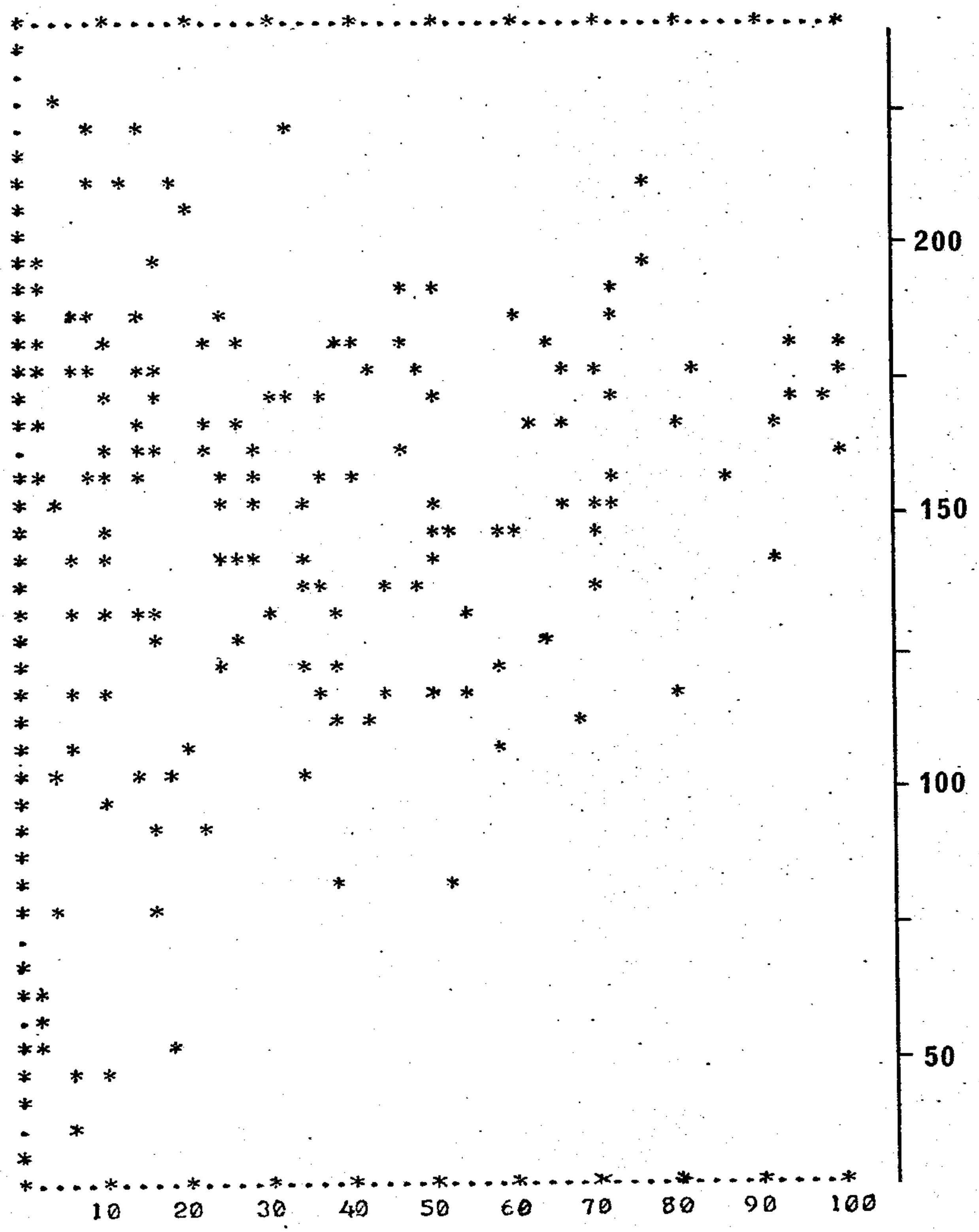


Fig 4.1 Stocking of parishes in GLU km^{-2} plotted against percentage of land in land class 1. Area supporting livestock taken as total area of temporary and permanent pasture, and rough grazing.

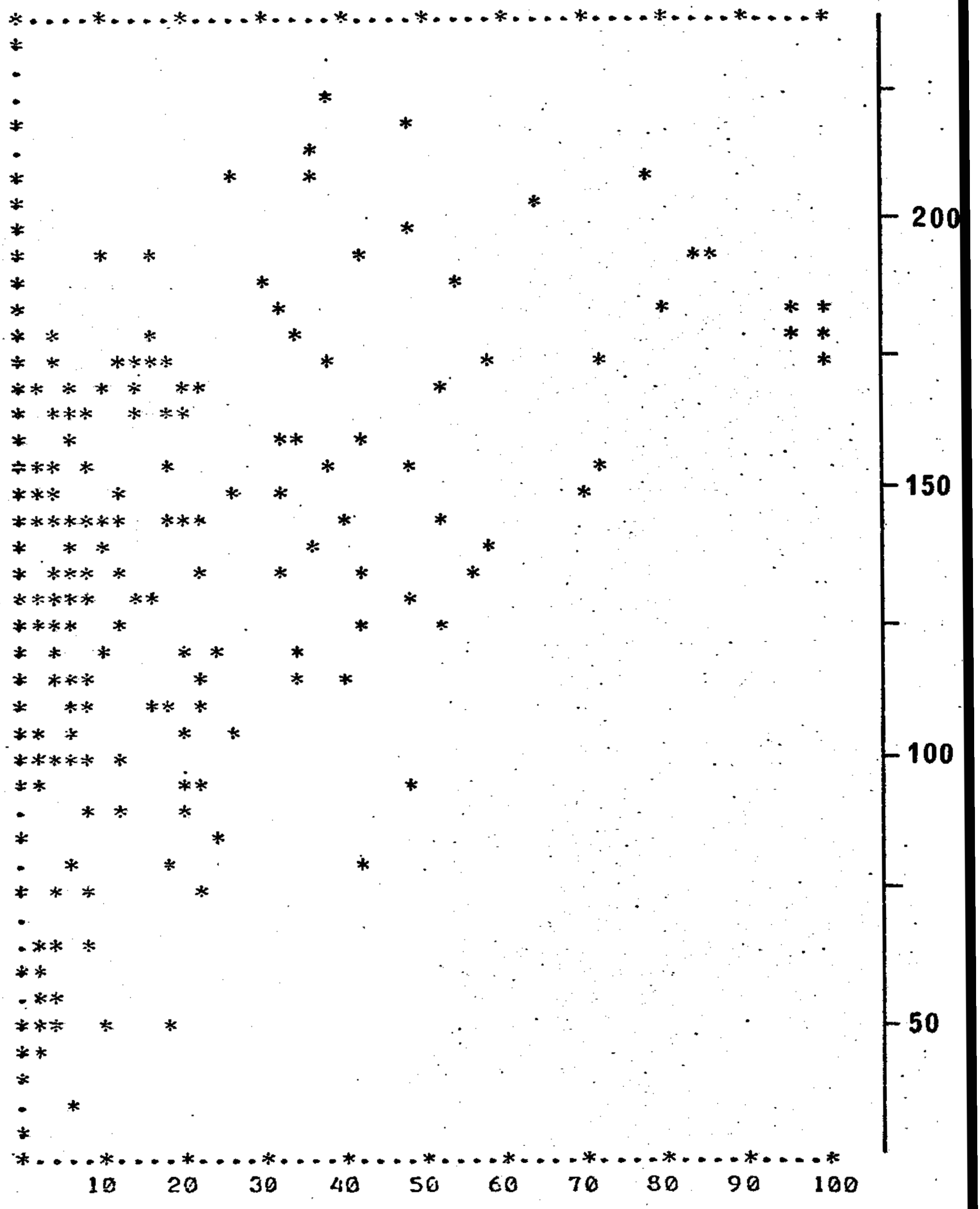


Fig 4.2 Stocking of parishes in GLU km^{-2} plotted against percentage of land in land class 2.

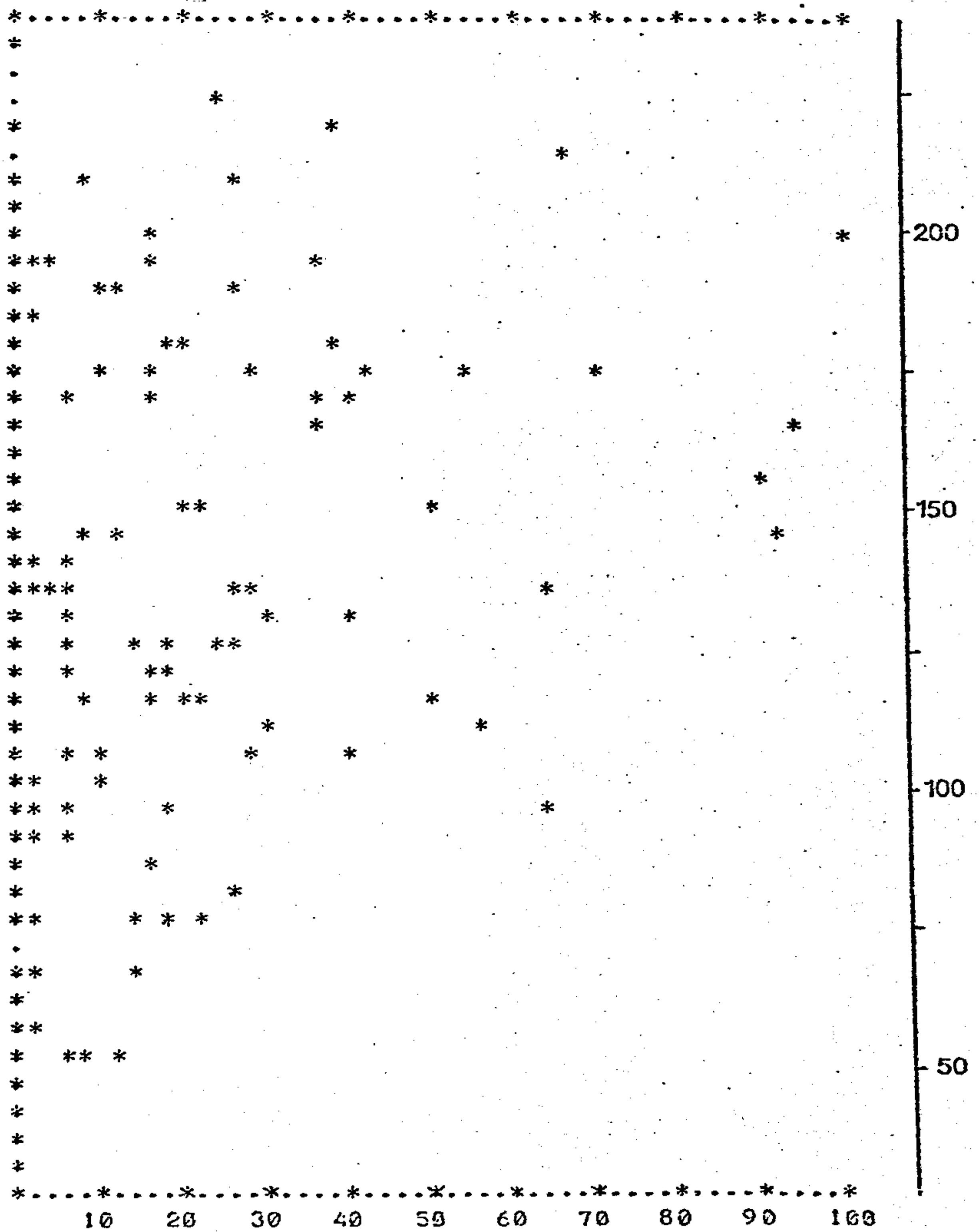


Fig 4.3 Stocking of parishes in GLU km^{-2} plotted against percentage of land in land class 3.

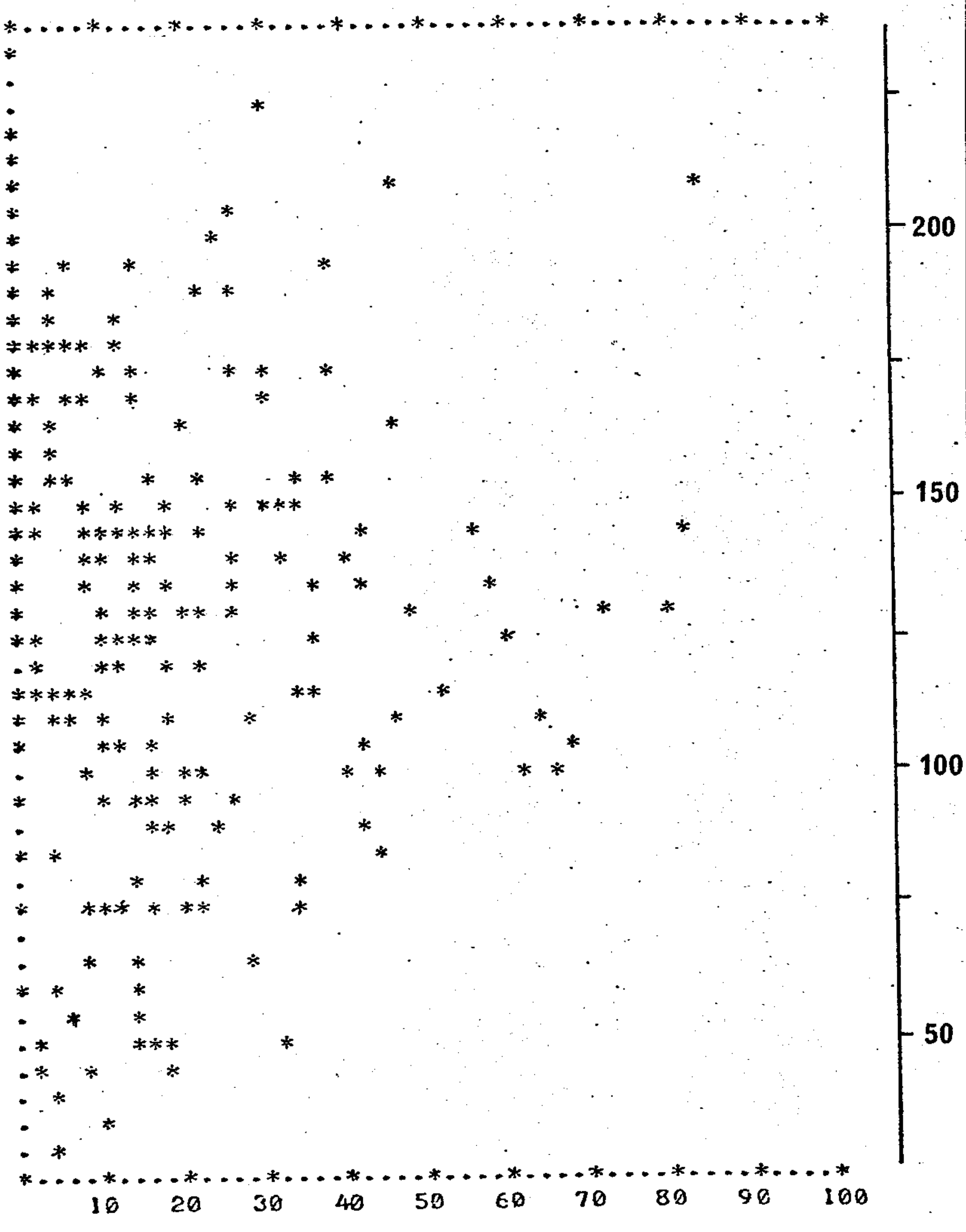


Fig 4.4 Stocking of parishes in GLU km^{-2} plotted against percentage of land in land class 4.

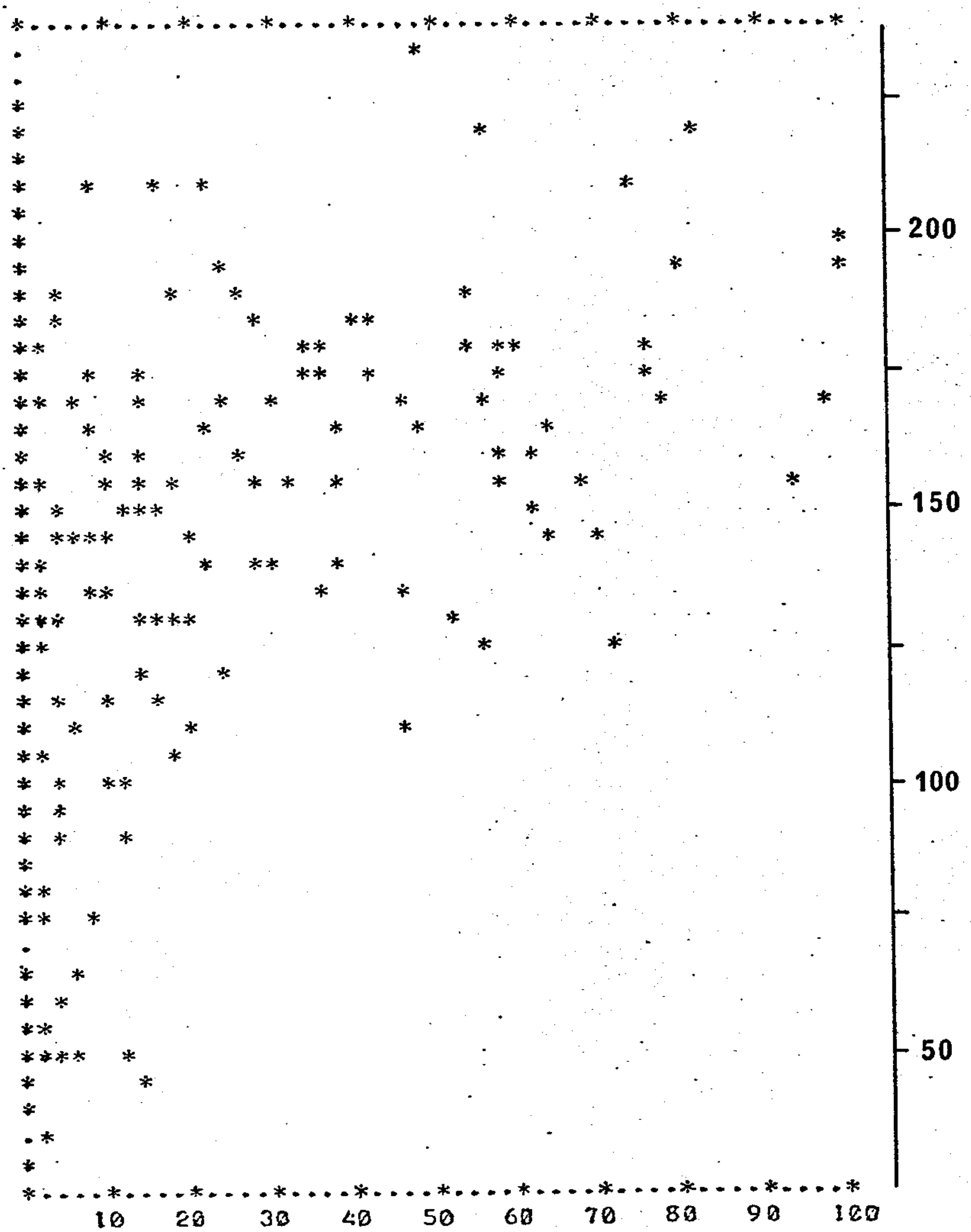


Fig4.5 Stocking of parishes in GLU km^{-2} plotted against percentage of land in land class 5.

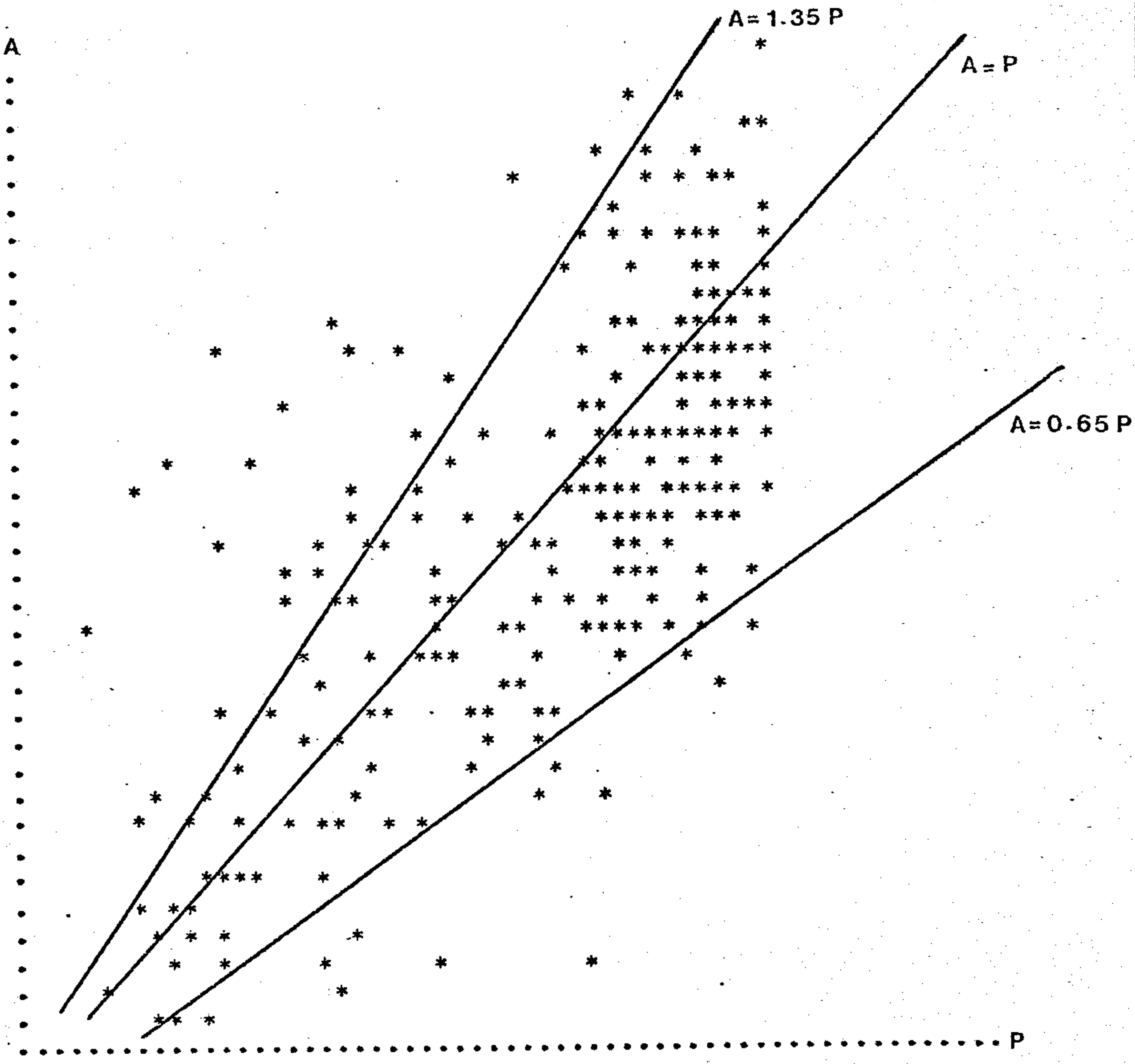


Fig 4.6 Plot of predicted parish stocking potential (P) against rates determined from Census returns (A).

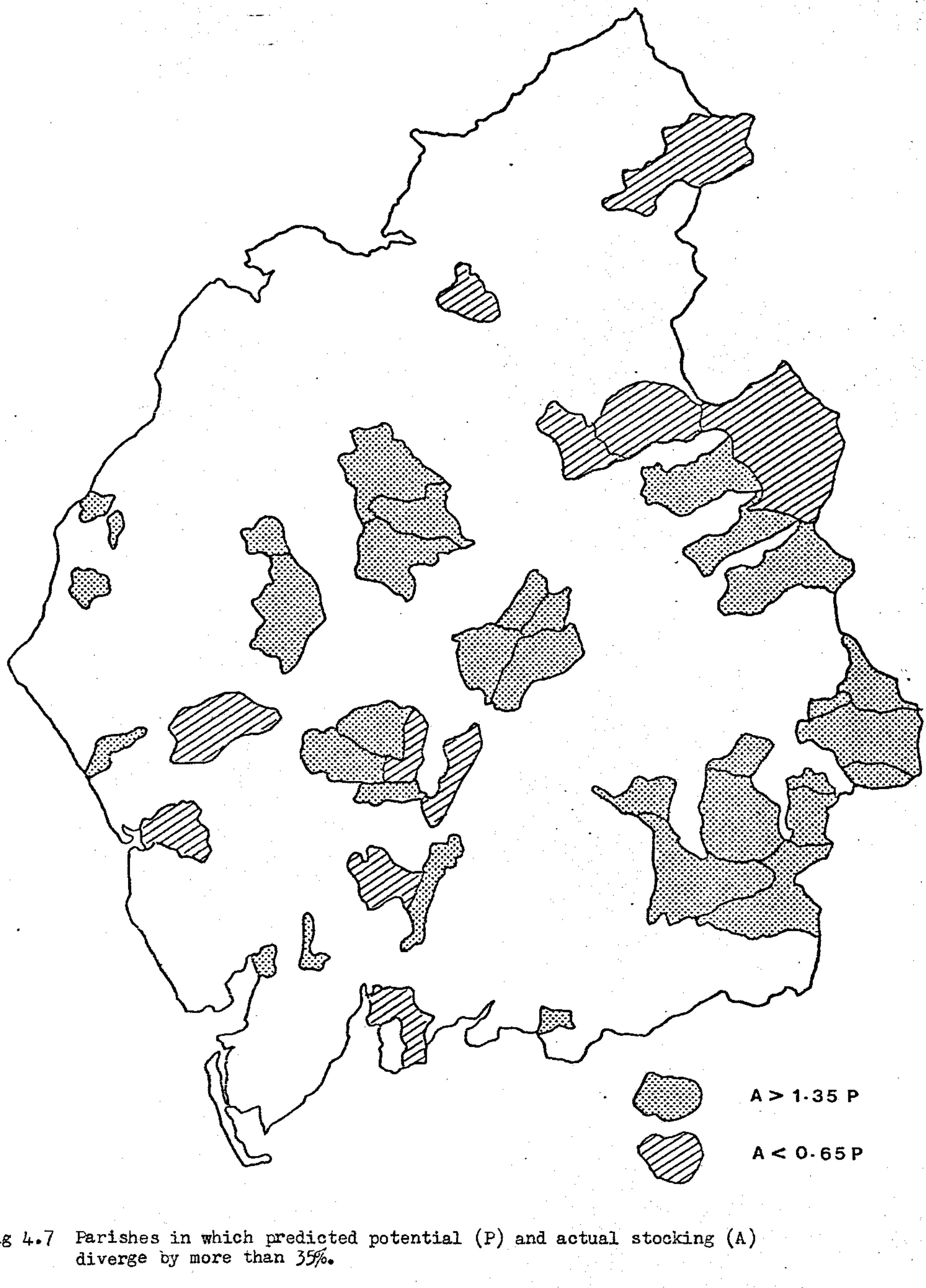


Fig 4.7 Parishes in which predicted potential (P) and actual stocking (A) diverge by more than 35%.

4.1.3 ASSOCIATED FACTORS - ECOLOGICAL VALUE, RECREATIONAL POTENTIAL

With every land use, every combination of inputs and outputs, there is associated value in the land as a provider of recreation (even if only as an agricultural landscape) and as an ecological reserve.

These factors are an important consideration for land-use planning, particularly in a county such as Cumbria, and if mathematical methods are to be applied to such planning then recreational potential and ecological value must be assessed numerically.

The value of an area of land in terms of (i) its potential for providing recreational activities, and (ii) its nature conservation status, depends on the inherent qualities of the local environment (climate, topography etc) and on the use to which the land is being put. In proposing a quantified assessment of these values the use independent and use dependent contributions are considered separately.

Ecological value

The generally accepted criteria of ecological value are summarised by Goldsmith (1975) as extent, naturalness, richness, diversity, fragility, representativeness, research and educational value, recorded history and potential value.

When considering widely distributed km-squares of similar character (i.e. a land class) it is the expected level of richness and diversity which can best convey the ecological value of the land. Naturalness is not a point for inclusion since we are considering the land only under well defined uses.

In fact it is the use which exerts the greatest influence on the ecology of an area of land. Use independent features which contribute to a lesser degree include soil conditions, climate and local habitat diversity.

Land use independent scores -

Information on contributors (other than land use) to the ecological condition is not readily available. In particular climatic values specific to the land classes in Cumbria cannot be estimated with great confidence. Nevertheless it was possible to draw up a table with scores for each land class under the following headings:

A. Soil pH - taken as the mean value of a total of 40 plots in 3 randomly selected grid squares in each land class (Heal, 1976).

B. Rainfall (mm) - estimated by inspection of a map of rainfall distribution in Cumbria 1976. (Cutforth, unpl.).

C. Temperature (day-degrees) - estimated by inspection of the corresponding map (of UK) in the Complete Atlas of the British Isles (Readers Digest).

D. Slope - a landscape survey (Benefield, in prep.) which was part of the I.T.E. Upland Land Use study recorded the average slope of 8 squares sampled in each land class (except 7 and 8). A total score for each class was derived by scoring the slopes as 1, 0-9°; 2, 10-19°; 3, 20-29°; 4, 30-39°; 3, 40-49°; 2, 50-59° and summing. The steepest and shallowest slopes would add least to the ecological condition. The most propitious environment is likely to be that with moderate - steep general slope with high variability in the pattern of erosion.

E. Water bodies - a score of 1 was assigned to each appearance of beck, river or lake attributes in the landscape survey.

In Cumbria areas of high ecological value are likely to be associated with low acidity, low rainfall, high temperatures, moderate slopes, and the presence of flowing or still water. A method of combining the figures for these environmental attributes into an index of likely ecological diversity was sought on the assumption that the relative importance of the parameters is ... pH > Rainfall > Temperature > Slope > Water bodies.

The value in the 'Combined core' column of Table 4.22 is given by

$$A - \frac{B}{1000} + \frac{C}{1000} + \frac{D}{20} + \frac{E}{20}$$

which implicitly weights the factors pH (2.8), Rainfall (1.5), Temperature (1.2), Slope (0.95), Water odies (0.60) when the range of their values is considered.

The final column of the table simply converts these scores into proportions of the highest scoring class, land class 6.

Land use dependent scores

Bunce and Smith (1977) have defined heterogeneity indices for 32 vegetation groups in Cumbria. Some of these vegetation groups can be linked to particular land uses and therefore indicate the relative heterogeneity of the plant life associated with those uses.

Insufficient samples were taken in any one land class to define diversity scores for the vegetation groups within that land class. The figures in Table 4.23 therefore represent the average diversity in that vegetation group in all the land classes in which it occurs. In some cases this use dependent diversity will vary from land class to land class as the nature of the prevailing vegetation changes. Thus, for example, sheep in the lowlands graze on a very different vegetation from those on the hills.

It may simplify matters to say that the land use dependent scores which will be derived here will not, in general, be land class independent.

The distribution of vegetation groups by land class is known (Table 4.1) and so the values of Table 4.23 could be translated directly into scores for the land classes as livestock support land. However, these scores are to some extent environment dependent and are a measure of diversity in their predominant areas of occurrence. For example, rough grazing land in the lowlands may have a quite different heterogeneity index from the upland rough grazing land on which the scoring is based.

The objective at this stage is to find the ecological value of various land uses which can combine with the use-independent scores. In the case of livestock the method of use varies from lowland to upland and the use-score should reflect this change. It therefore seems appropriate to assign scores to the agricultural grades as dividers between types of livestock farming. Using the relationship between vegetation type and agricultural grade given in Table 4.24, the diversity measures for agricultural grades are ...

Grade	2	3	4	5(sheep)	5(beef)
Heterogeneity index	3.5	3.8	6.5	6.0	7.0

... and from these the ecological score under livestock for each land class can be calculated.

As, in use-independent terms, land class 6 has the highest ecological value the usage score for other uses are given with this as a bench mark. Thus, while the vegetation survey would give heterogeneities of 3.9 and 2.7 to crops and potatoes the samples were made in land classes other than 6 and the values in class 6 must be 4.2 and 2.9 if the former result is to be achieved in classes 1 and 2 respectively.

The amount of woodland and forest sampling done by Bunce and Smith was small (since the area now in this use is small) and a comparison with agricultural lands was found in another survey ...

The report of the 1972 Dinas Conference (Farming and Wildlife Advisory Group) contains an analysis of sampling carried out in different habitat types on the Dinas estate in North Wales. The area under examination totalled 1317 ha and lay in the altitude range 152-488 m. The results are given in Table 4.25.

In relation to the numbers of insects present in the different habitats, the authors note:

> 'The number of insects occurring in certain of the older conifer plantations was very much greater than the number occurring in the oak wood. However, in most of these cases, the insects occurring in enormous numbers, such as aphids, Collembola, and Psocopters, are very tiny. The biomass (weight) of these insects might be the same as or less than the biomass of a smaller number of large insects occurring in oak. This point also applies to the large number of Collembola found in the ground litter of most of the habitats'.

If the densities of insects in the mature coniferous and in oak forest are taken as equal then Table 4.26 indicates the relative values in the seven environments. The overall score was derived by averaging along the rows giving each of the bird indicators half weighting. This gives equal importance to plants, insects and birds in the relative scores.

Now, from these scores new estimates of value for the forests can be derived. If we equate 'lowland fields' with 'improved pasture' then the implied woodland values are

$$\text{Coniferous} \qquad 5.2 \times \frac{0.57}{0.71} = 4.2$$

$$\text{Deciduous} \qquad 5.2 \times \frac{1.0}{0.7} = 7.3$$

If these are taken to be the values appropriate to land classes 4 and 9 which are of similar altitude to the Dinas forests, then land class 6 scores would be Coniferous 4.8 and Deciduous 8.3.

The ecological use-dependent scores for forestry and for cropping are not varied with land class, as are the livestock scores, because management practice is essentially the same in all land classes.

A set of scores for each use in each class is then given by multiplication of use-dependent and use-independent scores. These are multiplied by 10 to make the range convenient and the result is given in Table 4.27.

The Dinas figures also give a chance to check some elements of Table 4.27 where altitude and vegetation are of similar character. Thus, for example, the score for grazing in land class 3 should be comparable with the 'lowland fields' of the Dinas survey. It could be expected also that scores of roughly grazed land in classes 10-12 would be somewhere between the values of 'bracken slopes' and moorland. Table 4.28 shows that this is so although the figures of Bunce and Smith imply a higher moorland diversity in Cumbria than on the Dinas estate.

Recreational potential

Among the factors which must be considered when attempting to assess the recreational potential of an area of land are:

(a) community preferences with regard to

- (i) various recreational environments
- (ii) degree of contact with other recreators
- (iii) style of recreation

(b) the physical environment

- (i) the attractive or detractive features of the area
- (ii) the features of adjoining visible areas
- (iii) the ability of the area to absorb and withstand recreators
- (iv) the accessibility of the area

For the purposes of this study it was necessary to find a scoring system in terms of these factors not only for the existing land use structure but also for any potential land use distribution. The approach, therefore was to attempt to define a score for each land class in the county independent of land use and then to define a set of score ratios for land use independent of its physical setting.

The style of recreation preferred by the community will change and be changed by the physical environment. Recreational pursuits are tailored to suit the available facilities, while the facilities are extended to fit public aspirations. Quantification should reflect community preference for spending their recreational time in certain ways, and the ability of the area to support this distribution of preference: for example, an area with many roads will contribute more to recreation, if the public preference is for motor touring, than will an area with no roads. (The latter will contribute, however, if visible from roads outside the area).

Land use independent scores

The physical attributes of 14 of the 16 land classes were surveyed in 1976 (by ITE - Merlewood) as part of a study of landscape characteristics of the land classes. A field survey checked the presence or absence of attributes in 8 randomly selected squares from each of the land classes except 7 and 8. From the attributes checked in the landscape survey a smaller number were selected for this study. Those selected were considered to be land use independent and an intrinsic part of rural environment. They were divided into two groups, one representing natural features, the other being items of access and infrastructure - the human contribution.

In 1975, Cumbria County Council Planning Department prepared a recreational potential surface for the county. That is, they developed a scoring system which allowed each km^2 to be assessed quantitatively for recreational potential. As part of this work they conducted an opinion survey within the planning department which asked participants to rate various environmental attributes for their contribution to recreation. The results are given in Table 4.29

In addition to the individual attributes, an assessment of six categories of 'overall landscape character' was sought.

The scores derived through this survey formed a basis for scoring the attributes to be used in the present study. Unfortunately, while the C.C.C. considered the relative significance of attractive features they did not seek to rank in a similar way the detractive influence of various components of human infrastructure. A small group of people within Merlewood Research Station were questioned regarding the trade-offs they felt to be appropriate between the attractive and detractive features. This allowed the two to be treated similarly in later scoring.

Some of the members of the access/infrastructure list, while having a negative contribution as landscape features, make a positive contribution to recreation by providing access. In the C.C.C. study, access was considered only in terms of the presence or absence of a metalled road (other than motorway) in the km^2 being rated. In their opinion survey access was rated most important of all the features considered (a score of 90 in Table 4.29), but this is of little help in determining the relative contributions of access and natural features in creating the recreational potential of the land classes. The problem of access is further complicated by its dual nature. It may be considered in terms of macro-access (the routes enabling people to journey to a recreational area) and micro-access (the dispersion of people within the area). To introduce such considerations however embroils one in questions of distribution of recreational demand, travel times and distances - in fact in a major exercise in recreational demand. Here we are primarily concerned with recreation supply.

For simplicity it was considered the bigger the road, the greater the contribution to recreational access (the problem of the distribution of motorway entries and exits not withstanding). A table of scores (Table 4.30) was drawn up including all the selected attributes. Where there was no direct correlation between the attributes and those rated by the C.C.C. opinion survey the scores were interpolated as considered appropriate. One other change in scores from those given in Table 4.29 was made. This involved those attributes to which scale gives a special status. While an individual may feel that, for example, a large lake contributes little more to his/her recreation than a small one, the larger is able to contribute to the recreation of a considerably greater number of individuals. The scores assigned to 'large river' and 'large lake' were therefore doubled (the factor of two being entirely arbitrary).

The final score table then allowed the 14 land classes to be scored from aggregate attribute lists. The derived scores in the two categories are given in Tables 4.3. It can be seen from the column summations that the contributions of 'natural features' and 'access/infrastructure' to the total recreational potential score are about equal under the scoring scheme. Although there is no theoretical justification for this it does not seem unreasonable.

For land classes 7 and 8 it was necessary to estimate total scores. When a large sample of km^2 from the C.C.C. potential surface was examined it was found that the average score for squares in class 8 was very nearly equal to the average for the total sample. The average of Class 7 squares was about 0.75 of the overall average. This allowed the values shown in the table to be assigned for these land classes.

The question now arises of the influence of adjoining (and nearby) squares on the recreational potential of each other. Such influence as exists arises from the provision of middle-ground and distant views to the recreator in the square being scored. In general each square is surrounded by squares of similar character. Since overall landscape character has already been included in the scoring system it is arguable that the influence of adjoining squares is already implicitly present in the total scores.

Land use dependence

Among the scores in Table 4.29 are some that are directly relevant to assessment of the effect of land use on recreational potential. The value given to 'deciduous or mixed woodland', 'coniferous woodland', 'arable land or pasture' and 'bracken heath or rough grassland' reflect their contribution to the enjoyment of the individual recreator (or perhaps the small coherent group of recreators e.g. family group). It is also necessary to consider the capacity of these land uses to absorb or carry recreators. Two different factors influence this carrying capacity (i) the density of recreators which will so effect the environment as to change the most appropriate designation of land use and (ii) the density of recreators which so detracts from the enjoyment of each person in the environment that they fail to gain from their activities.

As an example of the first point it is clear that only a small number of people need walk through a potato patch before it is no longer a potato patch. Similarly a large traffic through upland grazing land may in time, unless suitably managed with paths, etc., be the cause of severely reduced grazing capacity through disruption of flocks or erosion following trampling. The different land uses may be graded according to their ability to withstand recreational pressures.

On the second point, there need not be many people in the potato patch before each begins to feel there are too many. To the person seeking solitude on the fells a single intruder into his/her range of vision may be too many. Again it is possible to grade the land uses by their ability to 'hide' people from each other (Table 4.32 shows both these gradings).

Before applying these gradings, however, there are other points that should be mentioned in relation to the development of scores for land use.

The importance of carrying capacity relative to other factors depends on the degree to which recreation is enjoyed 'inside' the use and how much the contribution is to someone 'outside' the use area. These terms are difficult to define. It might be thought that someone travelling in a car or coach or taking a picnic lunch in a car park or lay-by is outside the land use whereas someone strolling in a forest or stomping the fells is within the land use. However, the car traveller may prefer to be travelling a winding road flanked by trees than a similar road through grazing land, because of the seclusion this gives. In this sense he is inside the use. If the walker is treading well made paths and not affecting the productivity of the land then he might be considered to be outside the use. Thus, our definition of inside and outside depend on whether we are talking about carrying capacity in terms of the ability of the land to 'hide' or its ability to withstand pressure.

In the absense of knowledge of preferences regarding motor touring environments, or the determination of people to depart from established walking routes, the importance given to carrying capacity must be largely guesswork. The two carrying capacity factors for each land use given in Table 4.32 increase the ratio of best to worst scores for land use from around $2\frac{1}{2}$:1 to $4\frac{1}{2}$:1. If we consider all recreation to be outside the use then ratios should not change. If however, all recreation was thought to be inside then the ratio should perhaps be greater than this. The figures thus represent some split of public recreational preference.

We might perhaps vary the ratio with land class to reflect the fact that in the lowlands recreation is largely car based while land classes 13-16 contribute predominantly to walkers and climbers. The implication of this is that land use is a more important influence on recreational potential in the uplands than in the lowlands. On the other hand, since access to the uplands is lower the importance of carrying capacity os arguably lower. But as we are concerned with recreational potential it is reasonable to introduce some adjustment in scoring in line with the arguments above. Table 4.33 demonstrates this adjustment process.

Other points

Another factor to consider in scoring for land use is the compatibility of uses to landscape features, i.e. can one land use enhance some land forms while detracting from others? This again involves value judgements requiring the input of public and/or expert opinion. It is generally thought that there are conforming and non-conforming uses in landscape terms, and that the degree of suitability depends on management. For example the forest which is contoured to the land form is more compitable than one with straight, rigid boundaries. In some circumstances diversity may be generally regarded as a desirable landscape feature while in others the introduction of a new land use to an area may be thought an intrusion. No allowance for such differences of opinion was included in the coefficients. The point can be explored in running of the model.

Finally, the level of recreational demand depends in many areas on the proximity of 'service' centres - accommodation, pubs, shops etc. Near such centres or 'honey pots' the recreational carrying capacity of the land is more likely to be approached or reached than elsewhere. Again we are here concerned with demand rather than supply and development of this point is better left to the time of translation of results into policy.

The same applies to historic sites, stately homes and other points of attraction which are unrelated to the character of the land or its use.

Combination of factors

The final land use factors in each class were simply multiplied through the basic land class scores to derive scores for each class under each use. They were finally divided by 10 to keep the range convenient. Table 4.34 gives the result.

Table 4.22 Physical factors in ecological condition - by land class

Land class	pH	Rainfall (mm)	Temperature (day degrees)	Slope	Water bodies	Combined score	Ratio
1	4.9	900	2250	16	10	7.55	0.92
2	5.5	700	2200	9	4	7.65	0.93
3	5.6	850	1800	14	5	7.50	0.91
4	5.3	1300	2000	20	12	7.60	0.92
5	5.7	1000	2150	9	6	7.70	0.93
6	6.0	1000	2250	9	11	8.25	1.00
7	6.6	900	2300		No data		
8	6.2	950	2300		No data		
9	3.8	1500	1600	23	13	5.70	0.69
10	4.7	1500	1600	18	16	7.00	0.85
11	4.6	1350	1800	22	9	6.60	0.80
12	4.7	1350	1800	17	11	6.55	0.79
13	3.9	950	1300	28	11	6.20	0.75
14	3.8	1050	1100	17	12	5.60	0.68
15	4.2	1750	1300	26	9	5.50	0.67
16	4.0	2200	1100	22	13	4.65	0.56

Table 4.23 Heterogeneity indices of vegetation groups
(Bunce & Smith, 1978)

Vegetation groups	Description	Heterogeneity index
1-8	Cultivated	3.5
9-12	Improved pasture	5.2
13-16	Permanent pasture	8.0
17-32	Rough grazing* (beef	7.0
	(sheep	6.0
6-8	Cereal crops	3.9
5	Root crops	2.7
29-31	Broadleaf woodland	9.1
32	Coniferous forest	4.0

*The figure given by Bunce and Smith is 6.0 and this will reflect the present preponderance of sheep on rough grazing land. It is generally argued (e.g. Bocock & Adamson, 1976) that grazing of beef cattle is more advantageous ecologically than sheep. The figure of 7.0 is an attempt to quantify this difference.

Table 4.24 Assumed distribution of vegetation groups by agricultural grade

Agricultural grade		
2	100% Cultivated	
3	80% Cultivated	20% Improved pasture
4	53% Improved pasture	47% Permanent pasture
5	1% Permanent pasture	99% Rough grazing

Table 4.25 Results of ecological survey of Dinas estate

Habitat	Plant species per habitat Total	% of recorded	No. of insects in $100m^2$ (estimated)	Bird species pairs/acre	No. species
Deciduous Woods	464	69	172,734	3.7	31
Mature conifer	142	21	71,755 larch 217,320 spruce	1.2	15
Bracken slopes	286	42	2,702	1.2	11
Heather moor	100	15	32,748	.8	4
Grass moor	90	13	30,310	1.2	2
Lowland fields	302	45	-	3.1	22

Table 4.26 Normalised measures of ecological condition in different habitats

	A Plant variety	B Insect density	C Bird density	D Bird variety	E Overall score
Deciduous woods	1.00	1.00	1.00	1.00	1.00
Mature coniferous woods	0.31	1.00	0.32	0.48	0.57
Bracken slopes	0.62	0.02	0.32	0.35	0.33
Heather moor	0.22	0.19	0.22	0.13	0.20
Grass moor	0.19	0.18	0.32	0.06	0.19
Lowland fields	0.65	no data	0.84	0.71	0.71

Table 4.27 Coefficients of ecological value

Land class	Softwoods	Hardwoods	Use Beef	Dairy	Crops	Sheep
1	44	76	45	45	39	44
2	44	78	42	42	27	42
3	43	75	54	54	38	53
4	44	76	57	57	39	54
5	44	78	40	40	27	39
6	48	83	41	41	27	41
8	-	-	-	-	-*	-
9	33	57	48	48	48*	41
10	41	71	59	59	59*	52
11	39	66	55	55	55*	49
12	38	66	55	55*	55*	48
13	37	63*	53	53	53	45
14	33	56	48	-*	-*	41
15	32	56*	47	47	47	40
16	27	46	39	-	-	34

*These scores are for the alternate management options shown in Table 4.36-4.40 and described in Section 4.2

Table 4.28 Comparison of ecological values with scores from Dinas estate

If the score for deciduous woodland in land class 3 is set at 1.0 then comparisons are .....

Dinas 'Lowland fields'	0.65
Class 3 Sheep	0.72
Dinas 'Bracken slopes'	0.62
Class 9 Sheep	0.55
Class 11 Sheep	0.65
Dinas 'Heather moor'	0.22
Class 16 Sheep	0.45

Note: The Dinas scores are for vegetation only

Table 4.29 Recreational scores derived in Cumbria County Council survey

Attribute	Score	Attribute	Score
Metalled road	90	Bracken, heath or rough grassland	45
Major river or canal	50	Inland cliff	40
Small river or stream	45	Cave or pothole	25
Waterfall	55	Stately home, garden or historic site	60
Large lake (>100 ha)	80	Picturesque village	65
Small lake (<100 ha)	65	Footpath, bridle way or unmetalled road	50
Mudflat or estuary	35	Overall landscape character*	85
Sandy or shingle beach	75	Coastal and estuarine	0.8
Coastal cliff	55	Rolling lowland	0.5
Parkland	45	Low fells	0.65
Deciduous or mixed woodland	55	Rough fells	0.7
Coniferous woodland	35	High, wild limestone fells	0.7
Arable land or pasture	20	Lakeland craggy scenery	0.9

* These values were multiplied by the value 85 which had been scored as part of the whole attribute list. The different landscape characters were assessed separately, although in the same survey group.

Table 4.30 Attribute scoring table for recreation coefficients

Scores underlined were derived from the survey of Cumbria staff. The remainder are derived by interpolation or in conversation with Merlewood staff.

A. Natural features		Score
Overall landscape character		85
Land classes	7, 8	68
	1, 2, 5, 6	43
	3, 4, 11	55
	9, 10, 12	60
	13, 14	60
	15, 16	77

Attractive features

58.	Small beck (stream): slow flowing	20
59.	Small beck: fast flowing	40
60.	Small river: slow flowing	40
61.	Small river: fast flowing	45
62.	Large river	100
63.	Waterfall	55
64.	Natural lake < 0.4 ha	40
65.	Natural lake 0.4-4 ha	70
66.	Natural lake 4-40 ha	75
67.	Natural lake > 40 ha	160
120.	Near verticle crags 10-30m	30
121.	Near verticle crags 30-100m	40
122.	Near verticle crags > 100m	45

Table 4.30 (cont.)

B. Access/Infrastructure

		Value to landscape	Value to access
Roads			
127.	Motorway	-50	90
128.	'A' class: dual carriage way	-25	85
129.	'A' class: single carriage way	-15	80
130.	'B' class	-10	80
131.	Unclassified: fenced	-5	75
132.	Unclassified: unfenced	-	70
133.	Unmetalled: fenced	-	60
134.	Unmetalled: unfenced	-	55
Other			
138.	Railway BR	+5	-
139.	Railway - other	+10	-
140.	Railway BR overhead electric	-25	-
141.	Transmission wires: pylons	-50	-
142.	Transmission wires: poles	-5	-
143.	Above surface pipelines	-30	-
145.	Parking 5 - 50 cars	-25	60
146.	Parking > 50 cars	-50	90
169.	Nearest rail station < 3 miles	-	70
170.	Nearest bus route < 3 miles	-	70

Table 4.31 Land use independent scores of recreational potential by land class

Land class	Natural features	Access and infrastructure	Total
1	101	238	339
2	68	172	240
3	88	88	176
4	119	169	288
5	79	231	310
6	116	223	339
7			180*
8			240*
9	168	48	216
10	183	128	311
11	116	199	315
12	116	88	204
13	123	32	155
14	112	30	142
15	153	17	170
16	198	26	224
	$\sum$ 1740	$\sum$ 1689	mean = 241

* In taking a sample of scores from the C.C.C. study the mean score for L.C.8 was very near the mean of the whole sample. L.C. was about 0.75 of this score. This was used in determining the above scores.

Table 4.32 Land use dependent recreation scores

	Council survey	Carrying capacity Support	Hiding	Combined ratio
Deciduous and mixed woodland	55	1.2	1.4	4.40
Bracken, heath, rough grazing	43	1.4	1.2	3.44
Unused land	36*	1.4	1.3	3.12
Coniferous woodland	32	1.3	1.3	2.58
Pasture	21	1.1	1.1	1.21
Crops	21	1.0	1.0	1.0

* The score for unused land was assigned to fit the subjective final score given for such land in land classes 14 and 16 in Table 4.33.

Table 4.33 Modification of land use dependent recreational potential by usage pattern and land class.

The degree to which land use is important in setting recreational potential depends on the extent to which recreational value is gained from within the use or outside, for example from a motor car.

Estimates of the extent to which recreation is car based in each land class were made and a correction factor introduced. This factor is constructed so that the ratio for deciduous woodland to cropping should be 3:1 in lowlands and 6:1 on the hills and fells.

The figures for car usage and the endpoint ratios are not based on any hard data but are derived through conversation with people concerned with recreation in the county.

Land class	% Car based	Factor
1	80	0.59
2	80	0.59
3	25	1.15
4	60	0.79
5	80	0.59
6	80	0.59
8	25	1.15
9	25	1.15
10	25	1.15
11	25	1.15
12	25	1.15
13	5	1.58
14	5	1.58
15	5	1.58
16	5	1.58

So, the use dependent score for coniferous woodland in class 4 becomes
$1 + (2.58-1) \times 0.79 = 2.1$

Table 4.34 Coefficients of recreational potential

Land class	Softwoods	Hardwoods	Use Beef	Dairy	Crops	Sheep
1	59	102	38	38	34	38
2	42	72	27	27	24	27
3	49	86	22	22	18	22
4	60	107	34	34	29	34
5	54	93	35	35	31	35
6	59	102	38	38	34	39
8	67	118	30	30	24	30
9	60	106	69	27	69*	82
10	87	152	100	39	100*	118
11	88	154	101	39	101*	120
12	57	100	65	26	65*	78
13	54	93	62	54*	62*	72
14	50	60*	57	-	-	67
15	60	102	68	60*	68*	80
16	78	95*	90	-	-	105

Note:
(i) all lowland livestock has been scored as pasture
(ii) upland dairy has been scored as pasture
(iii) upland sheep have been scored as bracken, heath, rough grazing
(iv) upland beef have been reduced by $\frac{1.2}{1.4}$ because of lower recreation
recreation support capacity (mutual disturbance between cattle and persons high).
(v) scores marked * are for alternate management options shown in Table 4.36-4.40 and described in section 4.2

4.2 OTHER MANAGEMENT ALTERNATIVES

Management options which have already been mentioned and which are practised to some extent in Cumbria are (i) upland pasture improvement and (ii) the absence of management. The latter is a clearly defined situation and all inputs and outputs except recreational potential and ecological value drop to zero. The former, on the other hand, is a matter of degree. The effect of pasture improvement on the balance of inputs and outputs depends on

(i) the nature of the land, and

(ii) the type and degree of improvement pursued.

Feist et al (1976) list the ways in which an upland farmer can raise output and productivity as

(i) amalgamations

(ii) different farming systems

(iii) new technology ...

the last includes pasture improvements by correction of soil nutrient deficiencies, reseeding, bracken reduction, improved grazing management and, on better ground, drainage and more silage making.

Roberts (1973) has described the steps towards increased production by mountain pasture improvement in Wales. The pastures being improved are at altitudes between 500 and 560 metres and the betterment involves the application of limestone and slag, flail mowing, light cultivation, reseeding with ryegrass and clover, application of phosphate, potash and nitrogen, and rolling.

'The paddocks where pasture improvement has taken place are then grazed on a rotational basis, at an overall stocking rate of six ewes plus lambs per acre (improved plus unimproved acres within the paddocks) which, in practice, means a stocking rate of between ten and twelve ewes plus lambs on the improved areas for period of between four and five days, followed by a rest period of approximately fourteen days.'

The cost details of the improvement are given in Appendix 1 and show that over the whole estate of 838 hectares the gain in grazing capacity was 800 ewes and 20 cows, or 190 GLU. This is a gain of 22 GLU km^{-2}. Annual inputs necessary to sustain this gain are £10 ha^{-1} in fertiliser, £6.1 ha^{-1} in power and machinery, one extra man-year labour and about £2 ha^{-1} sundries. Using the energy conversions detailed in Appendix 2 the inputs (omitting sundries) amount to about 0.26TJ km^{-2} and 35 SMD km^{-2}.

The additional GLU as sheep would be 2.0 tonnes of meat, and 0.26 tonnes of wool in land classes 9-12 or 1.2 tonnes meat and 0.19 tonnes wool in classes 13 or 15. Beef in these latter classes would yield an extra 2.1 tonnes of meat. Land classes 14 and 16 were considered beyond improvement by this formula. Table 4.35 details these additional outputs and the necessary inputs.

The effect on ecological values and recreational potential of these changes in management are not easily assessed. Recreational value would be expected to decline as use intensified and the ability of the land to support recreation and maintain its productivity would conflict. In all classes improved sheep land is scored the same as unimproved beef, while improved beef is given the same score as coniferous forest. Ecologically the changes might be expected to increase the diversity and richness of the vegetation especially in sheep grazing land. The scores for these were increased to be equal to beef scores in the same land classes.

The option of leaving classes 14 or 16 as wilderness area would reduce inputs and outputs to zero and while ecological values would certainly increase (to the equivalent of deciduous woodland if that were possible), the recreational value of such an absense of management is debatable. The feeling in the Lake District National Park administration is that the recreational value would be lower than at present since the farming cottages, the dry stone walls and the sheep themselves provide considerable visual interest, while the close-cropping nature of the hills under sheep is also commonly appreciated. The limitation on access which is the result of grazing in these land classes is minimal.

Another variation in management is being encouraged by the National Park who wish to see farming continue in small-holdings. This involves some sacrifice of productivity particularly if the holdings are of less than 600 SMD (Edwards and Rogers, 1974).* The gain is predominantly in recreational potential through the retention of traditional agricultural landscapes and low intensity of operation.

Various hypothetical management options may also be examined. For example, forestry practice could be altered in a way that would reduce the timber yield but would increase the recreational and ecological value of the forests. Another possibility is a profound increase in the agricultural productivity of the lowlands brought about by, for example, investing more energy to grow a larger area of crops. Such a change would be accompanied by declining ecological values.

There are also trade-offs available between recreation and agricultural productivity, between labour input and energy input and so on. These could be explored through the model either singly or in combination.

The full set of coefficients of production including the improved pasture and wilderness options is given in Tables 4.36 to 4.40 while the alternatives in ecologic value and recreational potential have already been included in Tables 4.27 and 4.34.

*Although Waller (1971) might dispute this assessment, arguing that output per hectare is important, not output per man, whereas government policy is to encourage growth in the latter even at the expense of the former.

Table 4.35 Additional inputs and outputs associated with upland pasture improvement

	Land classes 9–12		Land classes 13 and 15	
	Sheep	Beef	Sheep	Beef
Extra inputs				
Labour (SMD)	108	105	109	105
Energy (TJ)	0.39	0.45	0.40	0.45
Extra outputs				
Meat (tonnes)	2.0	2.9	1.2	2.1
Wool (tonnes)	0.26	-	0.19	-
Food energy (TJ)	0.026	0.029	0.016	0.022

Table 4.36 Coefficients of meat production (tonnes km^{-2})

Land class	Beef	Dairy/ improved beef	Crops/ improved sheep	Sheep
1	25.0	21.4	-	16.7
2	26.5	22.7	-	17.6
3	22.8	19.5	-	15.2
4	19.8	17.0	-	13.2
5	27.9	23.9	-	18.6
6	27.9	23.9	-	18.6
8	25.0	21.4	-	16.7
9	5.3	8.2	5.7	3.7
10	9.9	8.5	8.9	6.9
11	9.9	8.5	8.9	6.9
12	9.9	8.5	8.9	6.9
13	3	5.1	2.9	1.7
14	1.2	-	-	0.7
15	3.6	5.7	3.3	2.1
16	1.4	-	-	0.8

Table 4.37 Coefficients of food energy production (TJ km^{-2})

Land class	Beef	Dairy/ improved beef	Crops/ improved sheep	Sheep
1	0.225	1.53	3.5	0.214
2	0.270	1.62	5.3	0.227
3	0.233	1.20	2.7	0.195
4	0.203	1.04	2.1	0.170
5	0.285	1.71	5.4	0.239
6	0.285	1.71	5.7	0.239
8	0.255	1.53	3.9	0.214
9	0.054	0.083	0.073	0.047
10	0.101	0.58	0.115	0.089
11	0.101	0.58	0.115	0.089
12	0.101	0.58	0.115	0.089
13	0.030	0.052	0.038	0.022
14	0.012	-	-	0.009
15	0.036	0.058	0.042	0.026
16	0.015	-	-	0.011

Table 4.38 Coefficients of energy consumption (TJ km^{-2})

Land class	Coniferous	Deciduous/ wilderness	Beef	Dairy/ improved beef	Crops/ improved sheep	Sheep
1	1.25	0.62	2.36	2.99	7.00	1.63
2	1.33	0.66	2.75	3.41	3.61	1.97
3	1.11	0.56	2.23	2.80	5.72	1.56
4	1.13	0.56	1.77	2.27	4.76	1.19
5	1.29	0.63	2.87	3.58	3.63	2.06
6	1.30	0.65	2.84	3.55	3.68	2.03
8	1.25	0.62	2.71	3.34	7.64	1.98
9	0.83	0.36	0.35	0.80	0.63	0.24
10	0.87	0.37	1.04	1.32	1.22	0.83
11	1.01	0.50	0.93	1.21	1.11	0.72
12	0.98	0.48	1.08	1.36	1.26	0.87
13	0.53	0.15	0.22	0.67	0.59	0.19
14	0.12	-	0.09	-	-	0.08
15	0.58	0.18	0.28	0.73	0.65	0.25
16	0.22	-	0.10	-	-	0.09

Table 4.39 Coefficients of labour requirement (SMD km^{-2})

Land class	Coniferous	Deciduous/ wilderness	Beef	Dairy/ improved beef	Crops/ improved sheep	Sheep
1	624	384	637	1062	255	501
2	659	400	771	1221	2855	627
3	562	358	586	974	231	462
4	571	358	490	828	213	382
5	642	390	817	1292	2900	665
6	646	395	787	1262	3035	635
8	624	384	713	1138	267	577
9	435	268	128	233	240	132
10	453	273	266	754	382	274
11	519	331	258	746	374	266
12	505	326	282	770	398	290
13	299	175	80	195	212	103
14	120	0	32	-	-	41
15	329	197	98	203	232	123
16	171	0	38	-	-	49

Table 4.40 Coefficients of milk and wool production (tonnes km^{-2})

Land class	Dairy	Crops/ improved sheep	Sheep
1	481		1.97
2	509		2.09
3	374		1.80
4	325		1.57
5	538		2.20
6	538		2.20
8	481		1.97
9	-	0.72	0.46
10	181	1.13	0.87
11	181	1.13	0.87
12	181	1.13	0.87
13		0.45	0.26
14		-	0.10
15		0.50	0.31
16		-	0.12

4.3 RELIABILITY OF COEFFICIENTS

A knowledge of the degree of error which may be present in the coefficients just defined is important, as later sensitivity analysis (Sec. 6.2.2) will demonstrate.

There are clearly as many difficulties in assessing the confidence limits of yields and productivities as there are in determining the best estimates themselves.

The problem of inhomogeneity of land in each land class is treated elsewhere (Sec. 6.1). Here concern is with divergence of numerical values from "typical" land in each class. Two types of divergence are readily separable conceptually. Error in estimation of, for example, meat production may arise from bad figures for herd composition or dressed carcass weights. In these cases the rated productivity of all land classes would be affected and all would contain similar proportional errors. If, however, the definition of yield classes (timber production) or GLU ratings (livestock carrying) by land class has been faulty then the relative values given to the land classes and perhaps even their rankings will be in error.

These must be assessed separately since an error which is common to one land use in all classes is less likely to affect the land use distribution preferred by the model than is an error confined to one class only. For example, if all the productivities of timber are 10% too low the optional land use distribution is unlikely to be affected; but, if just one class is rated 10% too low then it may be that this class is the most suitable for afforestation, rather than another previously recommended.

The coefficients are dealt with in the order in which they are incorporated in the model ...

<u>Timber production</u>

(a) Softwoods: The yield class estimated of Table 4.9 should be accurate to ±1 at altitudes below 450m. The translation of these to land classes is based on inadequate soil and altitude distribution data and uncertainty is certainly high. In classes 13-16 the unquantified factor of exposure becomes particularly important in determining yields. Uncertainty therefore increases with increasing altitude and the inter-use errors are estimated as

Classes	Uncertainty (m^3)	Percentage (Approx)
1-8	±30	2.5
9-12	±40	4.5
13 and 15	±50	12
14 and 16	?	50

In addition, the entire set of land classes would be ±10% from true yields.

(b) Hardwoods: Overall uncertainty is higher for hardwoods since few estimations of local yield exist and species are more variable. All values might be ±15% in error while intra-use error would be about the same in percentage terms as the softwood figures on which they are based. Possible divergence would be higher at increased altitude near the limit of the growing range.

Classes	Uncertainty (m^3)	Percentage (approx)
1-8	±15	3
9-12	±30	10
13 and 15	?	50

Meat production

The major uncertainty in estimating meat production is in the assignment of carrying capacities or stocking rates to individual land classes. The combination of Figures 5.1 and 5.5 and the distribution of agricultural grades (Table 2.4) allows reasonable confidence in lowland estimates. At higher altitudes, and in particular in the very variable upland classes, the divergence is possibly much higher.

Classes	Uncertainty (GLU)	Percentage (approx)
1-8	±10	6
10-12	±15	20
9, 13, 15	±5	16
14, 16	±2	20

In addition to this intra-use uncertainty these will be errors from inaccurate estimation of reproduction rates, cull rates, growth rates etc., used in compiling Table 4.19. These should be similar in all classes and are probably accurate to ±7%.

Food energy

(a) Livestock: Conversion factors for meat and milk to food energy are well known and so error should be no greater than that given under meat production.

(b) Crops: The ranking of productivity by land class is reasonably well defined but the productivity of the best land and the rate of decline are both tenuously based. The former gives an inter-use divergence of perhaps ±15% while the lower productive classes (3 and 4) may be an additional 20% in error.

Recreational potential

So many subjective evaluations are involved in setting recreational scores that estimates of error become fairly meaningless.

The effect of changes in certain valuations can be mapped through to the final score set and the reasonableness of these changes taken as a measure of the reasonableness of the corresponding changes in the scores. For example, if instead of using the "Access/Infrasturcture" scores of Table 4.30 these were divided by two to give a lower importance to the features included in this category, then the new score set is as given in Table 4.41. The differences between these scores and those in Table 4.33 are up to 30% and yet in neither case is the attribute weighting unreasonable.

There can clearly be very large divergences in recreational potential between the value used and that determined independently. Particularly in the uplands subjective considerations are paramount to the extent that the land use decision may rest on the personal, aesthetic preferences of the decision-maker.

Changes in environmental preferences or recreational patterns may also affect the recreational scores over time. Rescored ten years from now the values given may be considerably changed.

An assessment of accuracy cannot therefore be quantitatively given and results sensitive to recreational scores must be considered closely.

Energy consumption

(a) Timber production: Most of the energy used in timber production is for harvesting and milling. Estimates for both come from American sources without detail of the assumptions used. The harvesting figure may be as much as 0.1 GJ m^{-3} (40%) in error, while energy use in milling depends very much on cutting patterns and the general efficiency of procedures. Divergence from the U.S. estimates could easily be as great as 20% and so the inter-use uncertainty up to 25% overall.

Intra-use energy consumption errors will be no more than the errors in timber productivity unless there are very large differences in harvesting consumption in different land classes.

(b) Livestock: The energy inputs to various vegetation groups and to cattle are well documented by Leach (1976). These should not vary significantly from land class to land class and consequently intra-class error will be largely determined by and follow stocking rate inaccuracies.

Overall, the energy inputs to the land may be ±20% through problems of definition and interpretation of different pasture classifications. Input per livestock unit should be more accurate for cattle (±10%) than for sheep (±20%) since the latter are defined only by adoption of the former. There is therefore an inter-use uncertainty of ±15% in dairy and beef and ±20% in sheep.

(c) Crops: Estimates are based directly on UK average given by Leach (1976) and should be good to ±5%

Ecological value

The ecological values like the scores of recreational potential have no concrete meaning and so concepts of accuracy are dependent on the validity of the criteria used to define value as well as on the reliability of the data used in response to those criteria. The quality and quantity of data use may be increased but the criteria must remain to some extent subjective (although certainly less so than for recreational scoring).

With diversity and richness as the criteria of ecological value the absence of comment on the inappropriateness of the scores, from those who have been involved in this exercise so far, suggest that they are basically sensible. Since variations of 10% in many of the coefficients would make them clearly inappropriate (especially for intra-use comparisons) this is certainly an error limit of some kind.

However, possible error will be different for each individual score and its importance is probably best assessed in the light of accuracy requirements as revealed by sensitivity analysis.

Labour

(a) Timber production: Average labour requirements for forestry practices are known with apparent accuracy (Table 4.6). The separation of these into softwood and hardwood requirements, into urban and rural jobs, and the questions of road construction and transport, add uncertainties. Nevertheless any error should be no more than 10% in inter-use comparisons.

(b) Livestock: As with the energy inputs, agricultural labour requirements are extensively documents by Nix (1976). Any errors arise from difficulty with translation of farming terminology and practice into the greatly simplified categories of activity defined here. Inter-use divergence may be as much as 20% but intra-use comparisons should be close to 5% maximum error (taking stocking rates as correct).

(c) Crops: The input to wheat and potato growing are given by Nix (1976) and should be accurate to ±5%. Intra-use error will follow productivity.

Milk

The major uncertainty is in stocking rates as indicated for meat production above. There is no inter-use error since no land use other than dairying produces milk.

Wool

Again error will arise from uncertainty in stocking rates without any consideration of inter-use error being necessary.

An assessment of the error in a coefficient therefore depends very much on what it is being compared with. The error in an isolated coefficient may be high but as part of a set it may still convey information accurately. In these circumstances the units involved should perhaps not be taken too literally, but the coefficient sets taken as being a measure of relative input or output.

Table 4.41 Set of recreational potential coefficients derived by halving the access/infrastructure scores of Table 4.30

Land class	Use					
	Softwoods	Hardwoods	Beef	Dairy	Crops	Sheep
1	39	66	25	25	22	25
2	27	46	17	18	15	17
3	37	65	17	17	13	17
4	43	75	24	24	20	24
5	34	59	22	22	20	22
6	40	68	26	26	23	26
8	52	91	23	23	19	23
9	54	94	61	24	61	73
10	69	121	79	31	79	94
11	60	106	69	27	69	82
12	45	78	51	20	51	61
13	49	83	56	49	56	65
14	44	53	51	-	-	60
15	57	97	65	57	65	76
16	74	89	84	-	-	99

5. RESULTS

5.1 CURRENT PERFORMANCE

In Section 2 an estimate was made of the present distribution of land use by land class in Cumbria (Table 2.6). This combined with the input and output coefficients of each use in each class derived in Chapter 4 gives an estimate of the inputs and outputs of the county as a whole.

These cannot be expected to be identical to the measured produce of Cumbria. All afforested lands are not yet producing timber, stocking rates have been taken as the possible rather than the actual, and, of course, there is no pre-existing measure of recreational potential or ecological value. In addition to the total value of each factor as generated by the model Table 5.1 (a) gives alternative estimates where available.

Estimates of land use distribution were also made for the National Parks and the North Pennines AONB (Table 2.7). From these the outputs of these land units given the coefficients of Section 4 can be calculated (Table 5.1(b)).

5.2 POTENTIAL PERFORMANCE

There is clearly no one answer to the question: 'what is the county capable of producing?'. This depends on what the objectives are and to what degree each is pursued. It is possible to say, for example, that if the entire non-urban county were planted with coniferous forest (and the expanse not destroyed by pests) then the production of timber would be 6.2 million cubic metres. Similarly a figure could be calculated for wool production if the whole county were grazed by sheep but such have little meaning except as benchmarks.

If it is resolved instead that a certain quantity of food must still be produced while the objective is timber, then the model would recommend the area that should be assigned to food production while the remainder was forested. This is simple enough, since anyone would sensibly say that the best agricultural land should be used for food. Things become more complicated however when recreation, ecology and resource consumption are also important.

Suppose that the production of timber is still a primary objective but recreational and ecological values are to be maintained and some level of production of all agricultural products is required. How are these prerequisite levels to be determined?

The approach taken initially here is to set them at the level which the current land use pattern is capable of producing, as given in Table 5.1(a).

5.2.1 RESTRICTIONS ON LAND USE

In addition to these constraints the objective of timber production conflicts with the fact of the National Parks and the large AONB proposed for the Pennine strip. If it is determined, for simplicity, that land use within these areas and also Commons Land may not change from its present configuration (Table 2.7), then is it still possible to increase timber production?

Table 5.2 shows the possible changes in output (or input) of each factor under this constraint set. Thus, for example, county timber production could be increased by 43% over levels given by the present land use distribution. Similarly food energy (22%), milk (40%) and wool (23%) could all be increased by amounts which appear significant (the validity of results is discussed in the following chapter). The increases in timber and wool production are achieved with negligible changes in energy and labour input while the additional food energy and milk require 5% more energy input and 10% more labour.

It would be expected that as constraints are relaxed the potential for production of various commodities would increase since the range of options is increased. Table 5.3 is a pay-off table with no constraint on land use distribution, but with the output levels of Table 5.1(a) ensured. The greatest change is in the potential for timber production which could now jump to 134% above 'present' levels.

Table 5.4(a) follows this increasing potential through the stages of constraint relaxation: first the common land constraint, then the restriction on land use in the AONB and finally in the National Parks. The table shows that the major increase in timber production occurs with the removal of the National Parks as constraints. This is partly because their area is greater than the AONB or the external Common Lands and partly because they contain large areas of land classes 4 and 9 which the model suggests are the most suitable for coniferous afforestation (see below).

Some Common Land is outside the National Parks or AONB ($\sim$ 159 km^2) but most is within ($\sim$ 1020 km^2). Therefore, removal of the determination that land use on the Commons shall not change makes little difference to potential output levels on its own. If, however, the Common Land constraint were the only one in operation, then its removal would be much more significant. Table 5.4(b) shows that the potential for timber production rises only 19,000 m^3 when the Common Land constraint is removed, but those on National Parks and AONB are retained. However, in the absence of these Parks the opportunity cost, in terms of timber production of Commons is 74,000 m^3.

Also in Table 5.4(b) are the increases in the best achievable values of the other factors. The two Common land columns are already described; the given effect of the relaxation of the AONB constraint assumes the continuing existence of the National Parks, while the removal of the National Park constraint would remove all restriction on land use in the county.

Each of the possible changes given would not, of course, occur in isolation. As with the rises in timber production in Table 5.4(a) there would be increased energy and labour requirements and changes in other factors also. Using all these changes and the economic values estimated in Appendix 5 it is possible to suggest opportunity cost figures for the Parks and the Commons, or any other defined land use restriction.

The situation closest to present planning realities is probably that which includes the land use constraints imposed by the Common Lands, the AONB, and the National Parks (Parks and Commons). With output levels held to the present level the possibility of improvement by single objective was given in Table 5.2.

It is not easy to summarise the land use patterns which produce these improved outputs since they are very variable according to objective. Timber and meat are perhaps the two items which Cumbria is most looked towards for increased production.

The land use patterns which produce the possible 43% increase in timber production and 3% increase in meat production are given in Table 5.5(a) and (b). These are obvious similarities. Certain land classes are clearly preferred for certain uses. Dairy cattle appear best in land classes 1, 2, 5 and 8, beef cattle in 3, 4 and 8. Sheep are suitable to classes 2 and 6, and classes 11 and 12 with pasture improvement. The only available hill land is in class 13 and deciduous woodland/ scrubland is preferred here. Coniferous afforestation is best begun in classes 9, 11 and 8, and 2 or 4 depending on objectives.

Major variations from this pattern occur only when the objective is recreational potential or energy conservation. The former case requires large areas of deciduous woodland in classes 4 and 11 while the latter prefers beef to sheep in upland classes. To maximise ecological value the model gives a solution which includes the use of class 6 for deciduous woodlands.

In the case where no land use is fixed prior to optimisation the uses which are recommended under at least one objective for each class are:-

Class 1:	Beef cattle, dairy cattle and sheep
Class 2:	Coniferous forest, deciduous woods, dairy cattle and sheep
Class 3:	Beef cattle, dairy cattle and sheep
Class 4:	Coniferous, deciduous, beef, dairy, sheep
Class 5:	Beef cattle, dairy cattle
Class 6:	Deciduous woods, beef, dairy, sheep and crops
Class 8:	Conifers, beef, dairy, sheep
Class 9:	Conifers, broadleaves, sheep (incl. improved pasture)
Class 10:	Broadleaves, beef, sheep (incl. improved pasture)
Class 11:	Broadleaves, sheep (incl. improved pasture)
Class 12:	Conifers, broadleaves, (dairy), improved pasture sheep
Class 13:	Broadleaves, beef
Class 14:	Wilderness, beef, sheep
Class 15:	Broadleaves, beef
Class 16:	Wilderness, beef, sheep

Perhaps the most surprising absence from this list is that of sheep from classes 13 and 15 since this would be the predominant use in these classes at present. Beef only appears as the preferred use in these classes when the objective is a reduction of energy consumption. Otherwise, broadleaved woodland is preferred even though outputs are very small (equivalent to yield classes of 1.0 and 1.5). This appears to be largely the result of the recreational and ecological value of the land use. By contrast, sheep grazing has a higher recreational value than unmanaged land in classes 14 and 16 and is preferred under most objectives.

5.2.2 MANAGEMENT OPTIONS

The solutions discussed so far have been based on the coefficients derived in Section 4, which reflect current management policies.

The model may also be used to explore alternative management strategies which may be better suited to the achievement of some objectives.

<u>Low intensity forestry</u>

It is conceivable that forested land (coniferous) could be managed in such a way that although timber production fell by 25% per km^2, the recreational potential of the land would increase by 35% and the ecological value by 50%. The fall in timber production would mean a drop of 20% in energy requirement and 15% in labour (neglecting any employment flowing from the increased recreational potential). These figures are applied to coniferous forestry coefficients in land classes 1-12.

Retaining the land use restrictions imposed by the Parks and Commons and optimising for timber production gives the figures of Table 5.6(a). The large drop of 62,000 m^3 in timber production is accompanied by only small rises in recreational potential and ecological value. When the land use restrictions are removed, however, the situation changes and under the constraints the potential timber production is higher under the new, low intensity management system. The higher recreational and ecological value of the coniferous forests lowers the area of deciduous woodland necessary to preserve these qualities and allows the increased timber production to come from softwoods in classes 13 and 15. When the land use restrictions are applied these classes are not available for afforestation and so the increase in timber production does not occur.

The new management policy will also have an effect on the output potential of all other factors. The figures for meat production as the objective in Table 5.6(b) show that in the restricted land use situation the small drop in potential meat production is countered by a gain in milk production and a drop in energy consumption in addition to the recreational and ecological gains.

Clearly such significant departures from current forestry practice cannot be dismissed as 'uneconomic' since there are circumstances in which they can produce significant gains in terms of satisfaction of the full range of county objectives.

High intensity stock management

With a greater use of fertiliser and machinery, more of the lowlands could grow crops for stockfeed. A 40% increase in energy application per km^2 might produce a 20% gain in livestock productivity. However, there would be a drop in ecological value of perhaps 35%.

When these figures are applied in the restricted land use (Parks and Commons) situation, it is not possible to achieve present levels of all factors. The large area necessarily given to livestock and the drop in ecological value of that land makes maintenance of the overall ecological value impossible.

However, when land use is unrestricted all constraints can be met but at high energy cost as indicated in the pay-off table (Table 5.7). Under many objectives the maintenance of rural employment has now become an active constraint (whereas in other pay-off tables, labour requirement was generally in surplus) and potential output levels are being reduced by the need to maintain the labour input.

This result suggests that increases in agricultural productivity are not always beneficial and must be considered in context. The policy of the Lake District Special Planning Board of retaining small agricultural holdings derives from similar consideration.

5.3 TRADE-OFF DEFINITION

5.3.1 DUAL VARIABLES

As indicated in Section 3 the dual variables (the decision variables of the dual LP problem) indicate the trade-offs between objectives and constraints. Thus, for example, in the case of maximisation of timber production with present management and land use fixed in the National Parks, AONB and Commons, a change of one unit (1 tonne) in the constraint on meat production will change the potential timber production by 49.8 m^3. A relaxation of the constraint on recreational potential of one unit will allow timber production to be increased by 2.2 m^3.

These figures apply in fact only to the first movement in the constraint. They are the partial derivative (y/ S_i) and so do not necessarily apply to a change of a whole unit in the constraining value and certainly not to the changes greater than this.

When meat is the objective trade-off to the timber constraint is 0.018 tonnes m^{-3} and for recreation 0.070 units m^{-3} or 5.0 units tonne (meat)$^{-1}$. It is clear then that trade-offs are not internally consistant but vary with the particular situation being considered. Thus it is not possible to say that in county land use the choice is between 1 tonne of meat and 50 tonnes of timber, or 1 tonne of meat and 5 units of recreation, because under different objectives the choices will be different.

These will also change as land use options change. When there is no restriction on land use distribution the relationship between timber and meat is 68.4 m^3 tonne^{-1} under the timber objective, and 0.013 tonne m^{-3} under the meat objective. With recreational potential the changes are even greater, 11 m^3 unit^{-1} and 0.032 unit m^{-3} in the open land use situation.

Since the total available area in each land class is also constrained each class has an associated dual variable. Therefore if some land must be converted from rural to urban the dual variables are an indicator of lost production potential.

If the objective is food energy production then the loss of production for a loss of 1 km^2 of land from the land classes is as given in Table 5.8.

It may seem surprising that even though the actual food energy production capability of land class 16 is only 0.02TJ km^{-2} the loss in county production potential should be more than 3 TJ km^{-2}. This arises because of the redistribution of land use under optimisation. An additional km^2 of class 16 land has higher ecological and recreational value than lowland crop land, so any reduction of area in the class is effectively a tightening of constraints on these factors. Consequently lowland cropping must be reduced if the constraints are still to be met.

5.3.2 PARAMETRIC ANALYSIS

The relationships between constraints and objectives can be explored further through parametric variation of the constraining values.

If recreational potential has been maximised under present management and without land use restriction, what happens to that achievable maximum as increasing amounts of timber are demanded? The trade-off at the initial maximisation is given by the corresponding dual variable but this changes as the quantity of timber increases as shown in Fig. 5.1. Recreational potential drops more quickly per unit of timber as more is demanded. It appears however, to be very steady over a wide range of timber production levels at about 0.094 units m^{-3}. If within this range timber is valued at £7 m^{-3} the implied opportunity cost of recreational potential if £75 per unit. If recreational potential is valued at less than this (including returns from tourism etc), then more afforestation is justified. If the value is rated higher than such planting is not socially worthwhile. (This,of course, is a very simplified analysis which neglects multipliers, discount rates etc. as complicating factors).

In a similar way comparison in opportunity can be derived for a pair of monetary intangibles like recreational potential and ecological value (Fig. 5.2) or two more easily comparable factors like food energy and energy input (Fig. 5.3).

Two (or more) constraints could be varied simultaneously to give a three (or more) dimensional trade-off surface.

Available area may also be varied parametrically and production losses from land loss in different classes compared (Fig. 5.4).

5.4 MULTIPLE-OBJECTIVE OR GOAL PROGRAMMING

In most decision situations there is not one objective or factor to maximise or minimise, but a group of factors of relative importance which the decision-maker wishes to promote. A solution is sought which equalises the decision-makers' satisfaction with progress towards each objective.

Setting minimum output values for factors other than the objective is an attempt to provide a solution which reflects multiple objectives. So far these constraints have been set on the basis of present production rather than with reference to the possible. The latter may be a better guide to the decision-maker setting his goals.

In some decision-making situations a set of objectives may be combined into one by assignment of a common unit of measurement. This will frequently be a monetary unit and the objective to maximise profit. A value in £ per unit can be assigned to each of the factors used as objectives in this exercise. These values can be formed into a weighting system (Appendix 2). This weighting set is dominated by food energy production as the most 'economic' land use product and so optimisation for the multiple objective as defined by this set gives the same results as maximisation of food energy production. This would be a fair reflection of optimum land use for economic return if the additional food energy produced could all be sold at the price used to define the weighting. Verification of this assumption would require study of demand for the crop and dairy produce which make up the bulk of the county's food energy product.

Another approach to definition of a weighting set is described by Nijkamp and Rietveld (1976). If no constraints on output levels are set initially then the set of 'efficient' solutions is that which maximises each objective in turn. The output levels of each factor under the maximisations can be used to define a weighting set based on the implicit trade-offs between objectives. These weights then define a multi-objective function which can be optimised and the result presented to the decision-maker. On the basis of the output levels in this first solution the decision-maker may wish to impose some minimum achievement levels on the objectives (i.e. some constraints). A new pay-off table is generated by optimisation of individual objectives, a new weight set is defined and a new multi-objective solution generated. "This recursive process is terminated when a certain solution is accepted as satisfactory or 'ideal' by the decision-maker. The solution algorithm rests on a continuous interplay between experts and decision-makers". Table 5.9 illustrates this process.

The process may be begun with desired levels of achievement rather than acceptable minimums. In this case it is generally referred to as goal programming. The objective becomes a minimisation of scaled deviations from the goals. The diagonal elements of the original pay-off table may be chosen as the initial goals (as suggested by Benayoun et al (1971)) if the decision-maker is unsure of realistic desired levels.

The term programming is being used in fact for any variation of linear programming in which the 'single objective to be maximised or minimised really is composed of several goals". A notable example (Dane et al 1977) is its use in planning some 640 km^2 of the Mount Hood National Forest in Oregon. Up to 12 uses could be applied in each of 234 separately defined parcels of land. Goals related to sedimentation, water consumption, sewage outflow, traffic levels etc., resulting from growing population in the area.

It is clear that the model is capable of producing many figures relevant to Cumbrian land use. However, not all of these will be (i) reliable, (ii) of any interest to decision-makers now, and (iii) comprehensible.

Reliability is discussed at length in the following chapter; but further exploration of combinations of constraints, of variation of management schemes, of trade-offs between objectives or of weighting sets would be endless unless in response to specific issues or questions posed by an interested party.

The problem of result presentation is a binding one. Simplification of results to allow ready appreciation of major points may cause misinterpretation. Full presentation may be so complex that no conclusions are recognised by the decision-maker. To some extent this conflict may be eased by the use of diagrams (Fig. 5.5) and maps (Fig. 5.6), but again there are dangers in interpretation.

The best solution appears to be a complete understanding of the model and its output by the decision-maker. Failing this, contact between decision-maker and modeller must be frequent whenever results are being used for planning. The considerations of the next chapter reinforce this view.

Table 5.1 Input and output levels for present land use distribution
(a) whole county

Factor	Model estimate	Other estimates
Timber production (m^3)	331 600	
Meat production (tonnes)	81 700	64300[1]
Food energy production (TJ)	3 489	
Recreational potential	342 300	
Energy consumption (TJ)	10 600	
Ecological value	287 800	
Labour requirement (man-year)*	14 500	>14410[2]
Milk production (tonnes)	840 500	625000[1]
Wool production (tonnes)	2 680	1800[3]

*based on 250 SMD per man-year

[1] J. D. Cowie, MAFF. pers. comm.

[2] "Total farmers and workers" MAFF (Census 1974)

[3] Calculated on basis of total sheep and lamb population of 1.53 million

(b) Parks and Commons (as percentage of county levels)

	Nat. Parks	Nat. Parks & AONB	Parks & Commons	Commons
Timber	43	44	44	0
Meat	26	32	34	7
Food energy	20	22	23	2
Recreational Potential	47	64	67	28
Energy consumption	24	29	31	5
Ecological value	37	51	53	18
Labour	26	30	32	6
Milk	17	17	17	0
Wool	43	56	64	26

Table 5.2 Pay-off table with restricted land use options (Parks and Commons) (output percentage change from "present" levels in Table 5.1)

Objective	Timber	Meat	Food	Recr.	Energy	Ecology	Labour	Mills	Wool
Timber	+43	-	-	-	-	-	+2	+10	-
Meat	-	+3	-	-	+2	-	+2	+ 8	-
Food energy	-	-	+22	-	+4	-	+9	+38	-
Recreational potential	-	-	-	+5	-	+2	+1	+10	-
Energy consumption	-	-	-	-	-2	-	-	-	-
Ecological value	-	-	-	+2	-1	+2	+1	+10	-
Labour requirement	-	-	+20	-	+5	-	+10	+36	-
Milk	-	+1	+20	-	+5	-	+9	+40	-
Wool	-	-	-	-	-1	-	+1	+ 9	+23

Table 5.3 Pay-off table with no land use restrictions (output percentage change from "present" levels in Table 5.1)

Objectives	Timber	Meat	Food	Recr.	Energy	Ecology	Labour	Milk	Wool
Timber	+134	-	-	-	+ 6	+ 2	+ 9	+13	-
Meat	-	+8	--	-	+ 7	+ 5	+ 7	+11	-
Food energy	-		+49	-	+13	+ 5	+25	+58	-
Recreational potential	-	-	-	+11	+ 1	+ 8	+ 4	+13	-
Energy consumption	-	-	-	-	- 3	+ 3	-	-	-
Ecological value	-	-	-	+ 5	+ 2	+12	+ 4	+13	-
Labour requirement	-	-	+45	-	+13	+ 5	+24	+54	-
Milk	-	+3	+34	-	+13	+ 5	+19	+64	-
Wool	-	-	-	-	+ 2	+ 5	+ 5	+12	+56

Table 5.4 Effect of removal of restrictions on land-use

(a) all factor, timber objective

OUTPUTS	1	2	3	4	5
Timber (1000m^3)	473	492	590	774	332
Meat (1000 tonnes)	81.7	81.7	81.17	81.7	81.7
Food energy (TJ)	3490	3490	3490	3490	3490
Milk (1000 tonnes)	923	923	926	951	840
Wool (1000 tonnes)	2.68	2.68	2.68	2.68	2.68
INPUTS					
Energy (TJ)	10600	10600	10600	10600	10600
Labour (man-year)	14800	14900	15300	15800	14500
ASSOCIATED FACTORS					
Recreational potential (X.001)	342	342	342	342	342
Ecological value (X0.001)	288	288	289	294	288

1 Optimised with land used fixed in National Parks AONB and Common Land

2 Optimised withland used fixed in National Parks and AONB

3 Optimised with land used fixed in National Parks

4 Optimised with land used fixed nowhere

5 Output with present land use distribution

Table 5.4 (b) each objective function

	All Common Land	Commons outside	AONB	Nat. Parks
OUTPUTS				
Timber (1000 m^3)	74	19	98	184
Meat (1000 tonne)	2.2	0.2	0.9	2.7
Food energy (TJ)	270	70	190	680
Milk (1000 tonne)	15	9	45	149
Wool (1000 tonne)	.24	0.05	0.21	0.62
INPUTS				
Energy* (TJ)	23	5	20	61
Labour (man-year)	582	120	570	1380
ASSOCIATED FACTORS				
Recreational potential (X0.001)	6.8	0.4	5.9	15.6
Ecological value (X0.001)	13.8	1.3	9.2	17.6

*Possible savings

Table 5.5 Distribution of land use outside parks and commons giving

(a) maximum timber production

Land class	Softwoods	Hardwoods	Beef	Dairy	Improved sheep	Sheep
1	-	-	-	571	-	-
2	72	-	-	356	-	157
3	-	-	142	-	-	112
4	-	-	400	-	-	-
5	-	-	-	553	-	-
6	-	-	-	-	-	120
8	71	-	-	54	-	-
9	80	-	-	-	-	-
10	-	-	-	-	-	-
11	82	-	-	-	13	-
12	-	-	-	-	145	-
13	-	8	-	-	-	-
14	-	-	-	-	-	-
15	-	-	-	-	-	-
16	-	-	-	-	-	-

(b) maximum meat production

Land class	Softwoods	Hardwoods	Beef	Dairy	Improved sheep	Sheep
1	-	-	-	571	-	-
2	-	-	-	367	-	216
3	-	-	254	-	-	-
4	95	-	305	-	-	-
5	-	-	-	553	-	-
6	-	-	-	-	-	120
8	4	-	101	18	-	-
9	80	-	-	-	-	-
10	-	-	-	-	-	-
11	10	-	-	-	85	-
12	-	-	-	-	145	-
13	-	8	-	-	-	-
14	-	-	-	-	-	-
15	-	-	-	-	-	-
16	-	-	-	-	-	-

Table 5.6 Impact on objectives of low intensity forestry under
(a) maximisation of timber production

	Land use restricted		Land use free	
Management	Present	New	Present	New
Timber (1000m^3)	473	411	774	781
Recreational potential	342	350	342	342
Ecological value	288	292	294	296
Labour (man-year)	14850	14790	15830	15810

(b) maximisation of meat production

	Land use restricted		Land use free	
Management	Present	New	Present	New
Meat (1000 tonne)	84.4	83.6	88.1	88.1
Milk (1000 tonne)	911	916	931	920
Recreational potential	342	347	342	342
Ecological value	288	292	302	304
Energy consumption (TJ)	10760	10630	11340	11320
Labour (man-year)	14860	14770	15580	15520

Table 5.7 Pay-off table for high intensity stock management and no land use restrictions

Output (percentage change from "present" levels in Table 5.1)

Objective	Timber	Meat	Food	Recr.	Energy	Ecol.	Lab.	M.	W.
Timber	+121	-	+ 2	+21	+24	-	-	+16	-
Meat	+ 40	+6	+ 8	+15	+27	-	-	+24	-
Food energy	+ 39	-	+43	+16	+31	-	+11	+60	-
Recreation	+ 97	-	+ 5	+25	+24	-	-	+21	-
Energy input	+ 33	-	-	-	+14	-	-	-	-
Ecology	+ 61	-	+10	+18	+24	+2	-	+29	-
Labour	+ 40	-	+39	+16	+31	-	+10	+56	-
Milk	+ 39	+2	+35	+15	+32	-	+ 7	+66	-
Wool	+ 40	-	+10	+16	+24	-	-	+29	+36

Table 5.8 Dual variables relating food energy production to land class area

Land class	Loss of food energy production potential for each lost unit of land (TJ km^{-2})	
	Parks and Commons	No restrictions
1	7.07	6.21
2	7.09	6.21
3	6.97	5.10
4	6.59	4.87
5	7.30	6.73
6	7.38	6.82
8	7.01	5.99
9	4.92	3.72
10	6.30	5.59
11	6.09	5.62
12	5.82	4.58
13	4.33	2.91
14	3.42	2.16
15	4.17	3.28
16	3.15	3.30

Table 5.9 The approach to multi-objective interactive decision-making of Nijkamp and Rietveld (1976)

The decision-maker (i) accepts land use restrictions of Parks and Commons; (ii) decides timber production and food energy production are priority and sets constraints at 40% above 'present' values; (iii) is aware that there must be some loss of production of other factors and sets constraints for meat, milk and wool at 75%, 85% and 90% of 'present' levels; and (iv) decides to keep recreational potential and ecological values to present levels.

A pay-off table is generated and from it a set of weightings which produce the solution in column 2 of the table. The decision-maker decides that meat and wool constraints can be raised (column 3) as there is excess recreational potential and ecological value and energy consumption is low. The new pay-off table and weightings give a revised solution (column 4). Now the decision-maker feels that perhaps wool production is significant after all, but that since the Parks are not to be changed, ecological values in the rest of the county can be allowed to drop a little. He also decides that rural employment must be kept at a high level (column 5).

The process generates a solution with which the decision-maker is now satisfied (column 6).

	1 Original constraints	2 First solution	3 Changes to constraints	4 Second solution	5 Changes to constraints	6 Final solution
	(All outputs given as percentage of 'present' levels)					
Timber	140	144		145		140
Meat	75	75	86	86		86
Food energy	140	140		140		152
Recreation	100	107		102		100
Energy input	-	91		98		107
Ecology	100	105		100	97	97
Labour	95	116		118	118	118
Milk	85	91		109		85
Wool	90	90	97	97	105	105

Table 5.9 (Cont)

The land use distribution outside the Parks and Commons which gives this result is:-

Land class	Use (km^2)					
	Softwood	Hardwood	Beef	Dairy	Crops/ improved sheep	Sheep
1	4	-	-	567	-	-
2	12	-	-	-	260	313
3	-	-	135	-	-	119
4	163	-	237	-	-	-
5	-	-	-	553	-	-
6	-	-	-	-	120	-
8	9	-	-	-	114	-
9	80	-	-	-	-	-
10	-	-	-	-	-	-
11	41	-	-	-	54	-
12	-	-	-	-	145	-
13	-	8	-	-	-	-
14	-	-	-	-	-	-
15	-	-	-	-	-	-
16	-	-	-	-	-	-

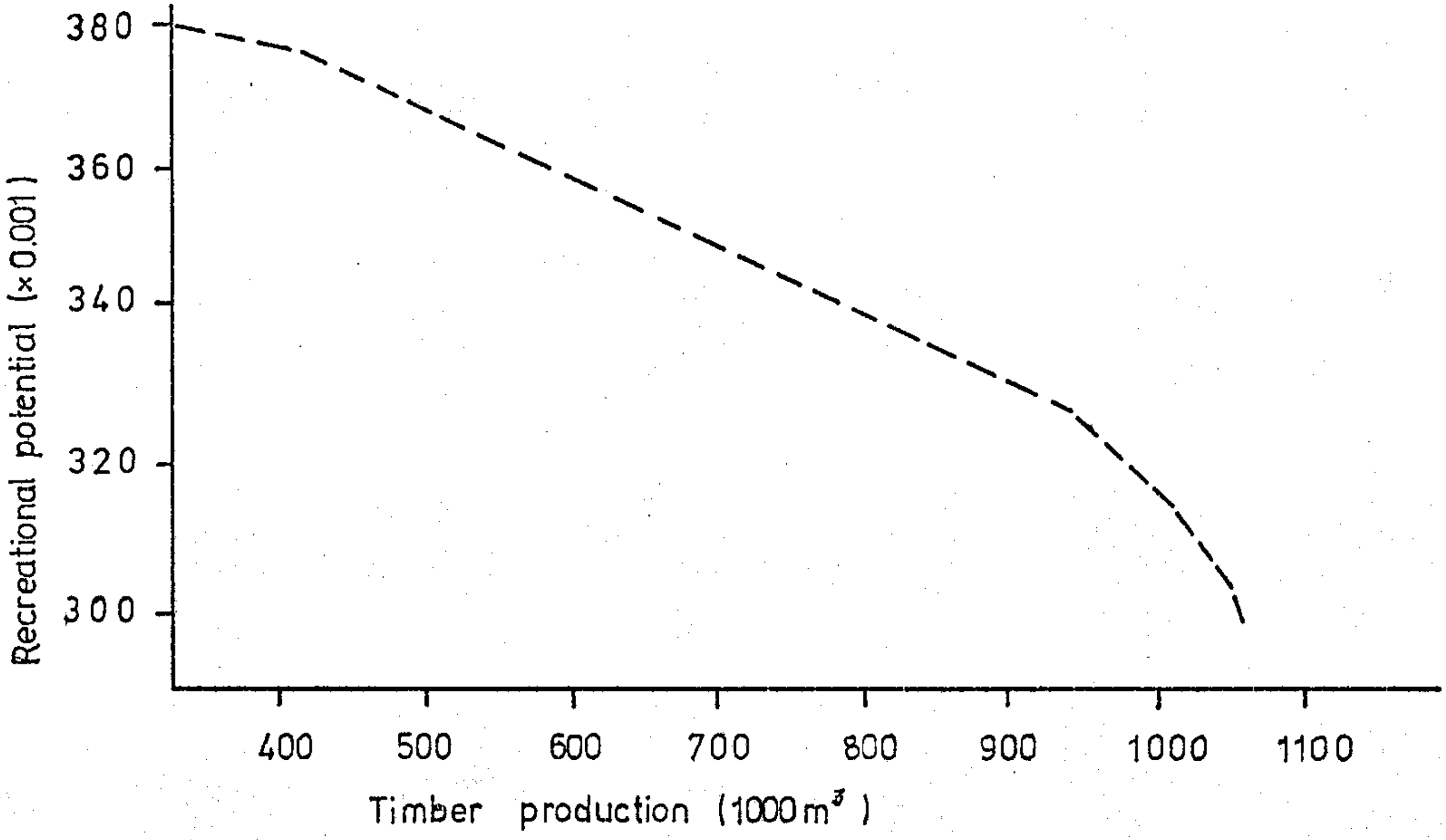


Fig 5.1 Trade-off curve for timber production and recreational potential. Land use unrestricted, other outputs constrained to "present" levels.

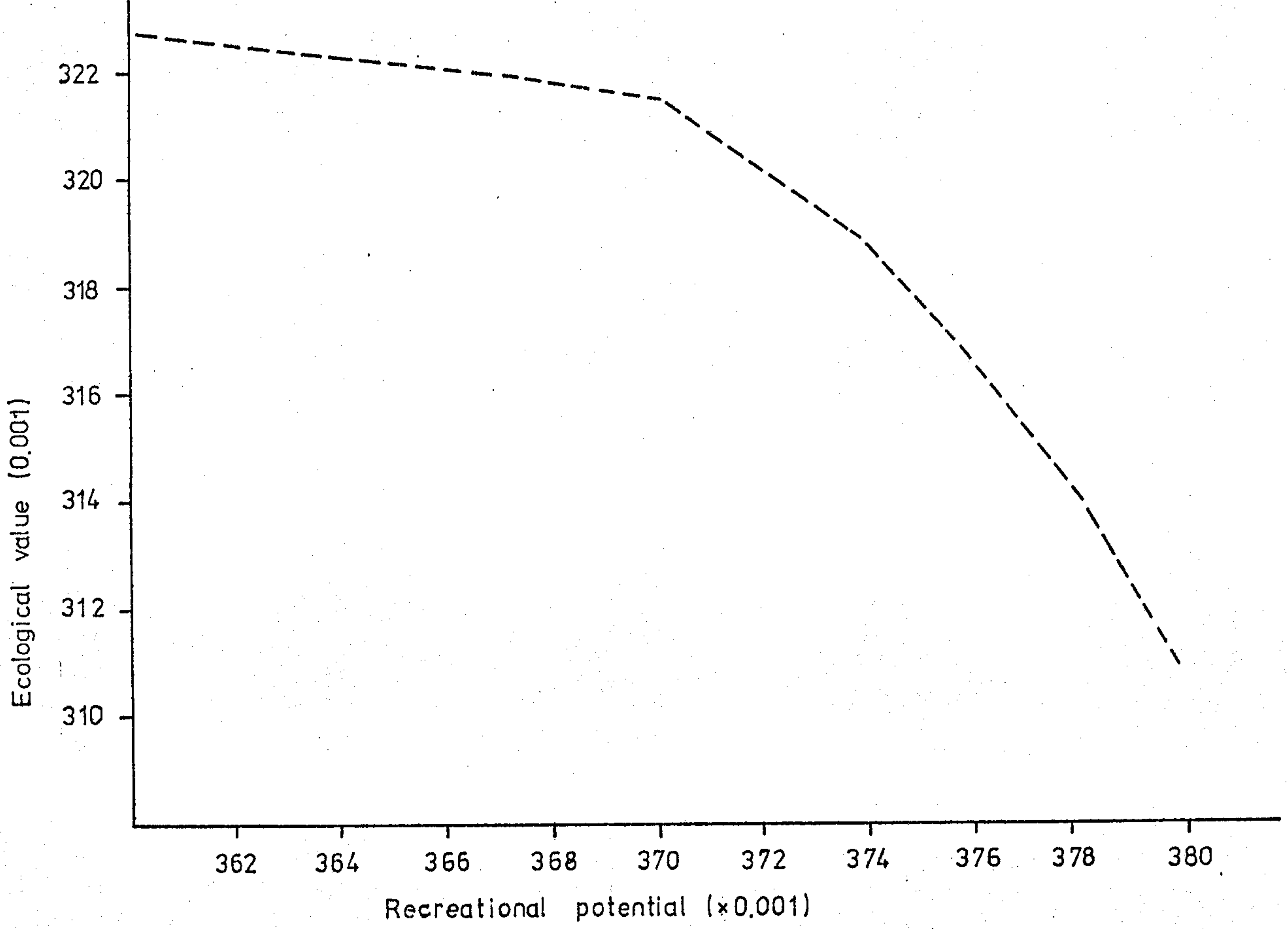


Fig 5.2 Trade-off curve for recreational potential and ecological value. Land use unrestricted, other outputs constrained to "present" levels.

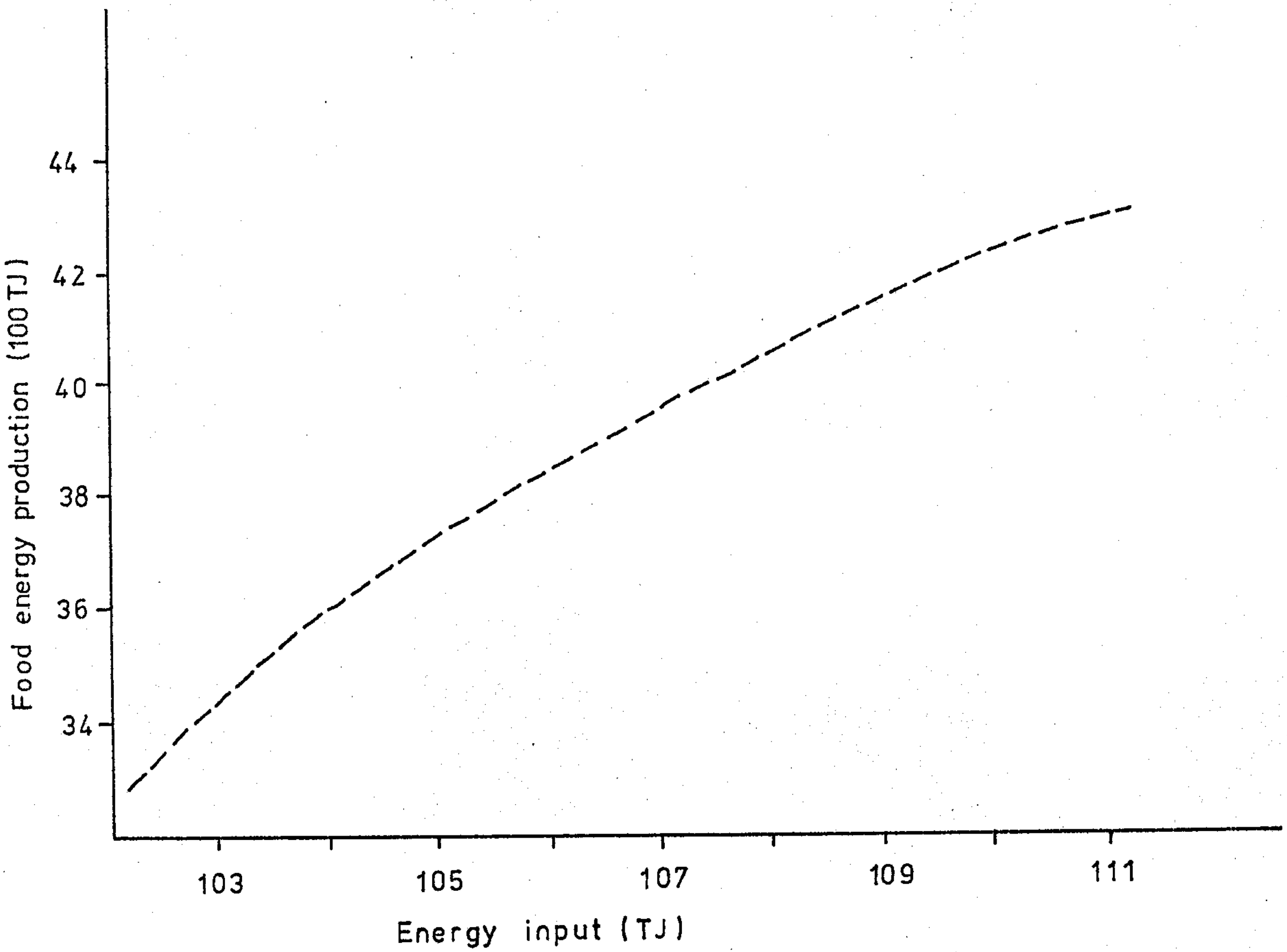


Fig 5.3 Trade-off curve for energy input and food energy production. Land use restricted (Parks and Commons) other outputs constrained to "present" levels.

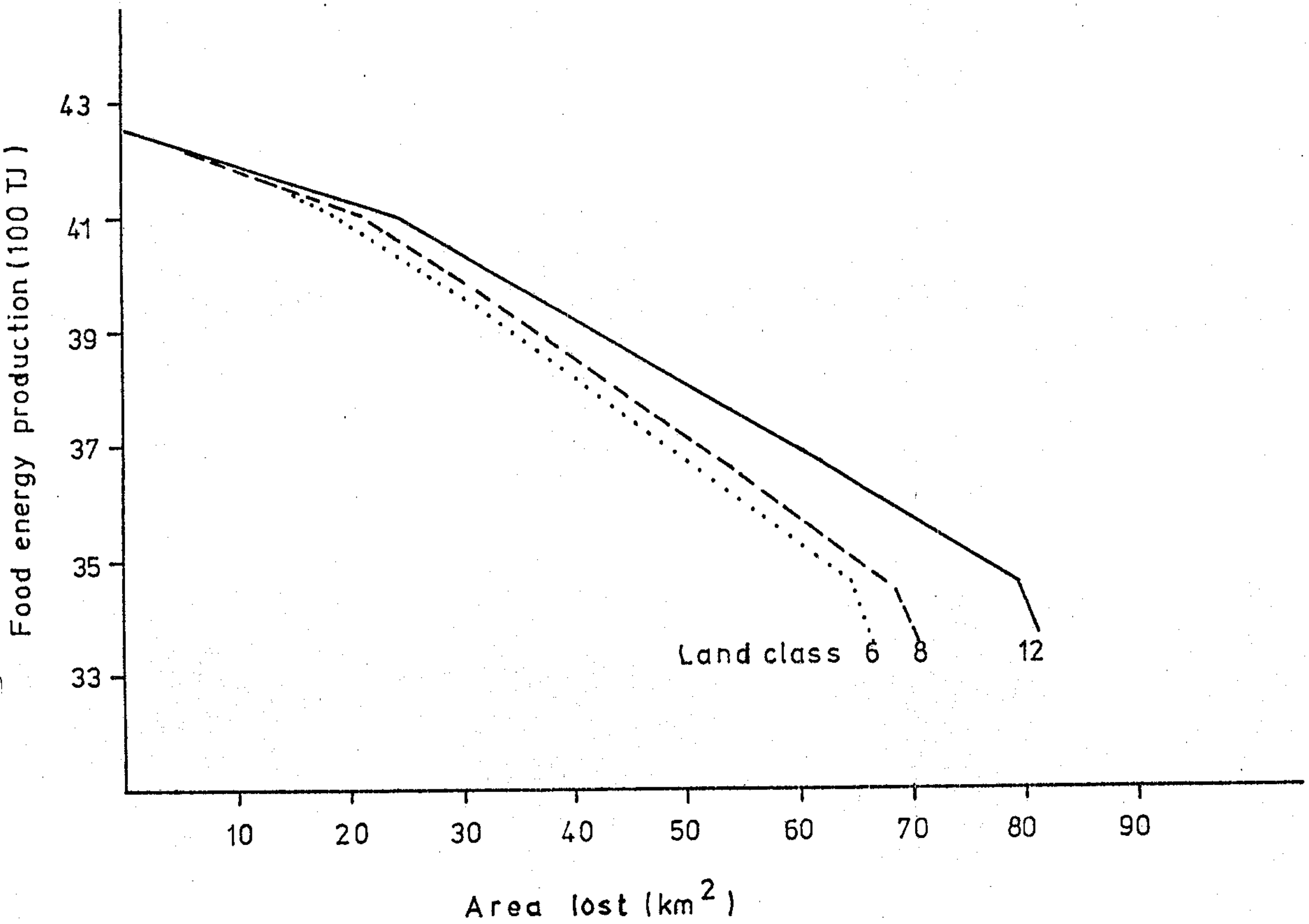


Fig 5.4 Reduction in potential food energy production as available land in particular classes decrease. Land use restricted (Park and Commons) other outputs constrained to "present" levels.

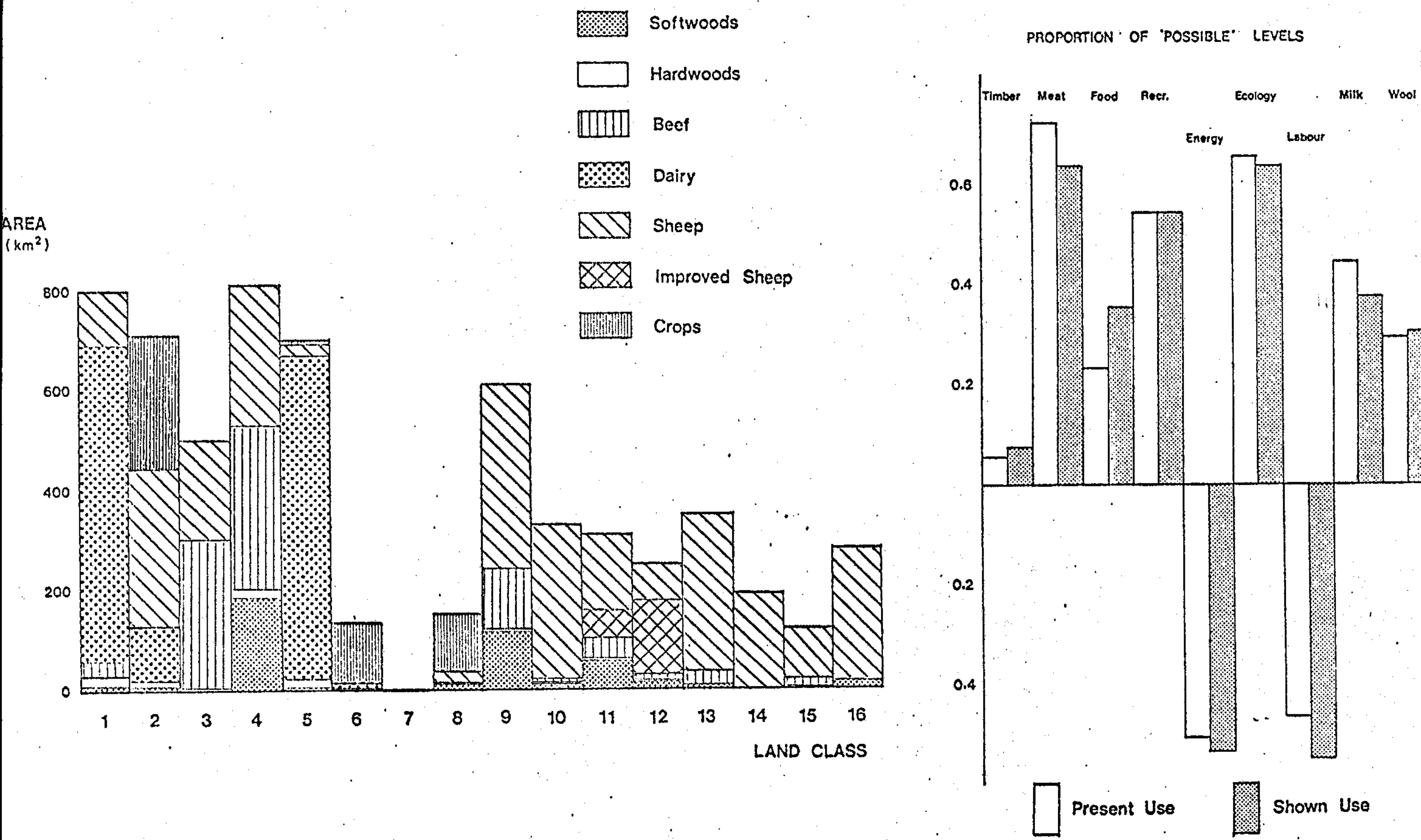
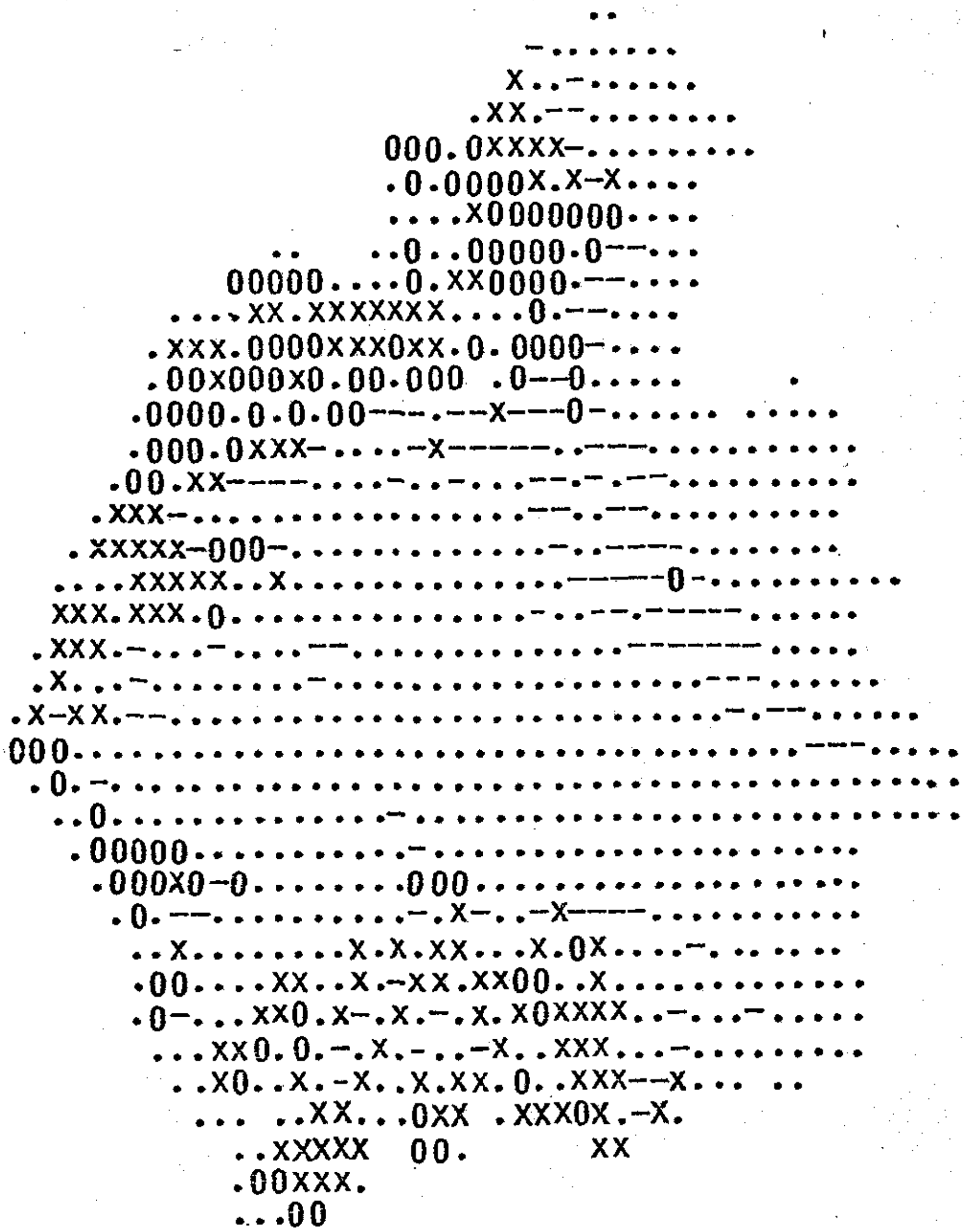


Fig 5.5 Graphical presentation of results. The "best" solution from Table 5.9.



.	:	1 to 14 %
–	:	15 to 28 %
/	:	29 to 42 %
+	:	43 to 56 %
*	:	57 to 70 %
X	:	71 to 84 %
0	:	85 to 98 %

Fig 5.6 Use of maps in result presentation. Distribution of dairy cattle throughout county under solution of Table 5.9.

6. RELIABILITY OF RESULTS

6.1 ASSUMPTIONS AND OMISSIONS

A great deal of simplification by assumption is built into the land-use model. This necessarily casts doubt on the validity of some or all of the results. Each assumption should be examined individually to determine

(i) its validity,

(ii) the degree to which any departure from reality will distort results, and

(iii) the chances of proceeding without making the simplifying assumption.

Linearity

The assumption of linearity is the most sweeping one in any use of linear programming. In the case of the Cumbria model it is simply a presumption against economies of scale and interaction between uses. That is, for example, 20 km^2 of coniferous forest in one land class will need 20 times the inputs of labour and energy that 1 km^2 requires; the larger area will produce just 20 times the quantity of timber and have 20 times the recreational potential and ecological value of the single square kilometre. There are clearly some departures from fact here although as 1 km^2 is the smallest unit being considered these should not be serious. One would expect that there might be some savings in energy and labour for harvesting if 20 km^2 of forest were continuous rather than scattered. In these circumstances however, the recreational value may be lower as scattered woods should provide ready access to a greater number of people. Ecologically the situation is less clear. Green (1977) writes: 'In general, the smaller an area and the greater its isolation from similar areas, the fewer species it will sustain. Also, many species, particularly predators, require very large territories to satisfy their food requirements'. At the same time it is certainly desirable to sustain a wide variety of habitat by maintaining each broad vegetation type in different physical environments or land classes.

In agriculture there would clearly be ecological advantages in mixed uses as distinct from vast areas of, particularly, crops. Proximity to markets and processing works will have a greater impact on inputs than any considerations of scale once farms are above a reasonable size (e.g. 600 SMD). Certainly 1 km^2 of one use is adequate for the employment of most modern agricultural technology.

The question of transport cost will be considered below and so the major divergence from reality in the linear assumption is in the inputs to and ecological value of forestry. The model does not prescribe particular sites for land uses except in so far as a large proportion of one land class in one use will generally mean large continuous areas of that use. Exceptions are the widely distributed land classes such as 4, 10 and 11.

Consequently where there are losses from too great an expanse of one use these are not recognised by the model. These will arise primarily in the recreational potential and ecological value and arguments against the use of a large part of one land class, e.g., coniferous forest must be considered. Where there are gains in some way from extensive singular use these can be considered as a bonus and should not seriously distort preferred land use patterns.

Since the model is based on categories of land rather than spatially defined areas there is no clear remedy for these distortions. Use of non-linear functions is of no advantage. The best solutions seem to lie in constraining certain uses to no more than certain percentages of sensitive land classes. Thus, it might be determined that no more than 20% of land class 2 be used for forestry.

Homogeneity of land classes

As mentioned at the beginning of Section 4 the land classes have been treated as homgeneous. In assigning coefficients it has been made to appear that all land in class 1 is agriculturally inferior to all land in class 2. The distribution of agricultural grades (Table 2.4) shows that this cannot be true.

If an area of land is to be divided in use between dairying and sheep grazing then popular wisdom would set the better land to the cows and allow the sheep the remainder. The constant assignment of dairying to land classes 2, 5 and 6 in the modelled solutions confirms this wisdom. Clearly, however, such model solutions will be a distortion since the best land available in the lowlands is not all in these classes. If 500 km^2 of lowland land is to be used for dairying then this should be the best 500 km^2 (neglecting cropping for the moment) irrespective of land class. This could be determined from maps of agricultural grade.

Similarly some model solutions recommend coniferous afforestation in the best yielding land class (class 2). This should be considered as a recommendation to use the best yielding land whichever land class it may be in. Problems arise here since the best agricultural land will in many cases also be the most productive land for forestry and priority must be determined. The model gives areas of land classes for each use and translation of these into specific land use policies will have to be done with an appreciation of the reasons for the model results if the usefulness is not to be lost.

It could be argued that this inhomogeneity renders the model useless. This is not so since in the county and indeed in each land class there is land which has (to good approximation) the characteristics suggested by the coefficient set determined for that land class. This is the land which should be used in the way given by the model and the model also gives the land class in which to look for such land.

The characteristics of the land are clearly multidimensional, but the variation within each land class might be represented as in Figure 6.1. Figure 6.2 gives a hypothetical example of the variation of a significant characteristic within 3 land classes. The extent of overlap between the Cumbrian land classes is clearly significant although reasonably well defined breaks occur between lowland (1-8), upland (9-12) and hill and fell (13-16). While the modelling should clearly be done on as many individually defined land classes as possible, interpretation may sometimes be best confined to these three categories. Distribution of land use within these categories could then be made on the basis of other distinguishing features always remembering the reasons for the model result.

To some degree this problem would be overcome by incorporation of these additional distinguishing features into the model. Definition of a larger number of land classes either by continuing the indicator analysis (see Appendix 1) or perhaps by labelling such as 'Land class A agricultural grade C' giving a number of sub-classes within each class. These sub-classes would be more homogeneous with respect to their agricultural potential and would be no less (and possibly more) homogeneous with respect to recreational potential and ecological value.

Productivity changes

Changes in agricultural productivity in the two decades prior to 1970 included gains in wheat yield from 2.4 tonnes ha^{-1} to 3.5 tonnes ha^{-1}, in average milk yield per cow from 2.5 tonnes to 3.8 tonnes, and in overall production of 35%.

Such changes in agricultural or silvicultural productivity, particularly if not uniform between land classes, will seriously disrupt the conclusions of the model. Some commentators on future land use in Britain (e.g. C.A.S., 1976) assume that this gain in agricultural productivity of 2% p.a. will continue indefinitely. This may be a best assumption but it is certainly not a safe one; Powell (1971) writes ...

> 'Enormous advances in mechanisation, the massive application of synthetic fertilisers, herbicides and pesticides, and new plant varieties have given British agriculture a record in productivity second to none in the world. But this increased efficiency has been bought at a high price. Evidence accumulates to force home the fact that the soil on which we depend for so much of our own food will not tolerate the unremitting exploitation which has been brought about by ever-increasing economic pressures'.

Even without the prospect of soil depletion through over-use there is the possibility that productivity could decline through either (i) the continuing consumption of good land for urban use, or (ii) a return to more labour intensive agriculture as energy costs rise faster than labour costs and standards of living (as conventionally measured) decline. (This latter might in fact provide gains; see Waller (1971)).

While the model includes the possibility of productivity gains from pasture improvement in the marginal lands of classes 9-13 and 15, there is no simple way to include sweeping but unpredictable changes in the general direction of agriculture. However, by modelling with a wide variety of possible productivity sets, the preferred land use pattern under each can be examined. Some conclusions may then be possible concerning the distribution of land use which will provide a good result for productivity status quo. Similar considerations will apply to changes in social values as discussed below.

Costs of land-use change

To change land from one use to another entails costs in labour and energy. These may be small for a shift from one livestock group to another but quite appreciable if removal or establishment of forest is involved.

Depending on the means by which such changes were effected, the cost would also involve inconvenience or disruption to those working the land (a social cost), or compensation to them (an economic cost). Neither of these types of cost is included in the model but both are significant.

In fact, there is unlikely to be a decrease in the forested area of the county in any foreseeable future. The Forestry Commission is planning for 180 km^2 of new afforestation in the U.K. each year and private forestry interests expect similar plantings (C.A.S., 1976). Cumbria will be expected to take a fair proportion (perhaps 5%) of this.

Certainly existing commercial plantations will not change use until at least the end of their first cycle. However, the areas involved here are quite small (400 km^2) and to constrain these to their existing use will not greatly affect the model results. Non-commercial deciduous woodland is still shrinking in the county as trees age, and contiguous grazing prevents regeneration. While this is a problem in amenity terms it has no serious consequences for the modeller.

As stated afforestation is proceeding over large areas as land is acquired for this purpose. Should it be decided that areas for afforestation be chosen on the basis of land class rather than availability then the social and economic costs in acquiring the land would be increased. The more profitable the uses already being undertaken the higher these costs are likely to be since the greater will be the land holders' aversion to change.

The major problem is therefore a social one and difficult or impossible to quantify. Even allowing a long time period for the proposed land use changes is unlikely to remove this difficulty. It would be possible to set limits on the allowable degree of changes from existing land use patterns or to set absolute limits on the area given to particular land uses in particular land classes. But to do this arbitrarily without consideration of the reasons why the model has suggested a contentious land use pattern would be to prejudge the issues. It is more appropriate to examine such a solution and the constraints or objectives which have produced it in the light of social (and political) arguments. Then, if necessary, additional constraints may be imposed on the model.

Transportation costs

The siting of an enterprise will affect its transportation requirements. The pre-existence of milling or pasteurising works will affect the economics of an individual (or corporate) choice of land use. To an extent these facilities tend to follow the uses but they will tend also to be sited near major transport routes and population centres for economic reasons.

This imposes little or no problem in land classes 1, 2, 5, 6 and 8, which are never far from such services. In the other land classes, particularly 13, 14, 15 and 16 there will be additional labour and energy costs arising from their relative remoteness. These differences have not been accounted for in the model.

In order to assess the significance of this omission it is necessary to make some estimates of the costs involved. In forestry, most of the milling of Cumbrian timber is done outside the county (Fanstone and Himsworth, 1976). The transport cost will increase with distance from major exit points. For example, if the average extra travel distance from land class 15 is 10 km each way then, using the figures of Table 6.1, the additional energy requirement would be 0.02 TJ per 1000 m^3 or 2% of the total energy demand. Similarly the additional labour requirement will also be just 2% of that for other work. Again for 20 km, figures for milk and for stock transport are very similar. Energy requirements per GLU are only 0.6% and 0.2% respectively of overall figures per GLU. Additional labour requirements are just 0.8% for milk and 0.2% for cattle of the normal work load per GLU.

While these extra costs may be important in siting a particular enterprise they can be omitted from the model without seriously affecting conclusions regarding general land use patterns.

Mixed land use

It is recognised that in some areas the introduction of trees will allow increased stocking rates in addition to supplying some timber. Recreation coupled with agriculture or with forestry also constitute mixed uses. In the model recreational values of each use have been scored but (i) no allowance has been made for joint agricultural and forestry use, and (ii) the mix of productive and recreational priority have been held constant in all uses.

Despite the obvious advantage of mixing agriculture and forestry, particularly in marginal grazing lands, little use has been made of such management in Cumbria. This is partly the result of shortage of capital and partly the reluctance of farmers to experiment with new practices. On some large estates where shelter belts and scattered trees have been placed in grazing lands gains have been substantial.

There are clearly also ecological and recreational (through landscape enhancement) advantages in this mixed use. Certainly this option should be in the model and would equally certainly replace the straight grazing options (in most solutions) in those land classes where it can be used. In the model then it would not be so much an alternative use as a replacement for the existing sheep and beef uses. Considered in this way the only changes necessary would be to raise the output coefficients of beef and sheep grazing and to include some timber output from these uses.

Quantifying the trade-offs between recreational potential and agricultural or forestry productivity is also difficult. Two farmers in the Hartsop Valley (Feist et al., 1976) attempted to give their losses resulting from recreational pressures. One reported losses of £600-700 p.a. and the other estimated that he had spent 1600 hours p.a.

repairing essential walls. These losses are however not definitive of loss in grazing capacity of the land. In heavily used recreational areas such loss is certain but little effort has been made to quantify any relationships. Forestry Commission opinion (pers. comm.) is that the recreational use and usefulness of their forests can be increased considerably with minimal loss of timber production. Grizedale is a frequently cited example. In the county council opinion survey on which the recreational score for coniferous forests largely rests, it is not clear what concept of the forest respondents had in their minds when rating the various land uses. It could be said that management such as at Grizedale, which encourages recreational use, is not in fact raising the recreational potential of the forest, but merely providing facilities to complement the existing potential. The recreational potential of the forest is raised by less dense planting, species mixing, contoured edges, roads and rides etc. Use of these options does lower productivity but again no quantitative link has been has been attempted.

In each of these cases not only recreation and productivity are involved but also the labour and energy requirements and the ecological value. Theoretically these changes could all be plotted against each other and relationships derived which would fit into the model and so provide a solution which included the optimum balance in, for example, forest management for productivity and for recreational and ecological values.

Omission provides therefore not so much a distortion of results as a narrowing of options. These options need to be better defined before they can be programmed into the model.

Economics

Little attempt has been made in the work to translate the effects of land use policy into monetary units. The output of any commodity is taken to be of value despite the effects that additional production might have on prices (especially, for example, on potatoes). The value of the multiplier associated with each output is also disregarded. As indicated in Appendix 2, prices may be used in establishing weightings for the outputs (and inputs) in defining a multiple objective function. In fact this is the only stage at which economic factors can and should be brought into the analysis.

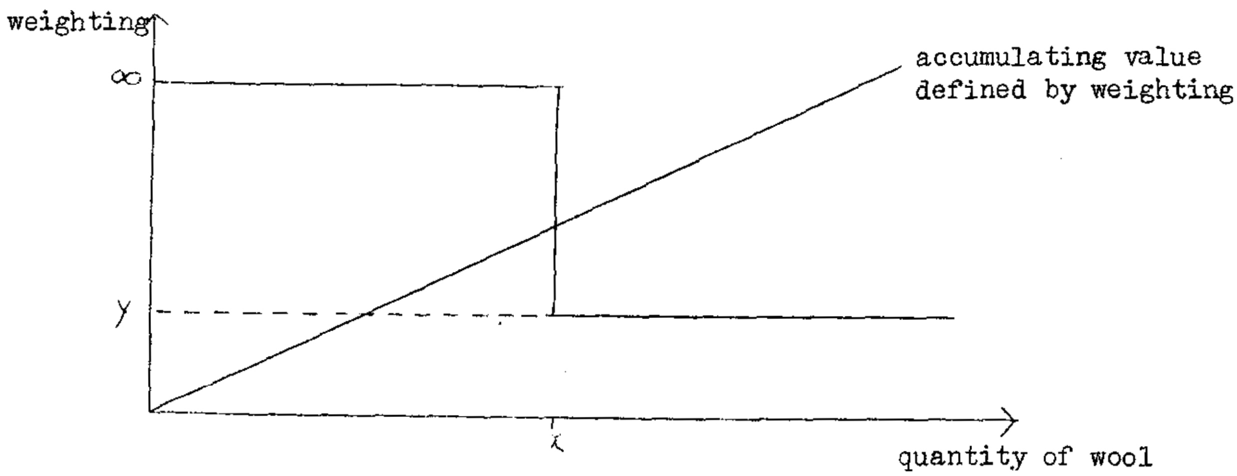
Each activity, each product, will generate additional employment and income, but this will, in general, be urban based and thus not a direct consideration in planning rural affairs. The exception to this is recreational potential. Work towards realisation of this potential will be predominantly based in rural areas. This potential employment which follows is not included in the model because while the creation (or conservation) of a potential for recreation may require some small labour component (e.g. repairing stone walls) the large quantity of employment is servicing the tourist and recreation industry is not created automatically but follows the demand for such services. There we are concerned only with the supply of areas for recreation not the level of demand for them.

Values

Since the solutions produced by the model depend on the constraint set imposed, each solution represents a value set. Indeed, the structure of the model itself necessarily reflects the values of the modeller. This is unavoidable.

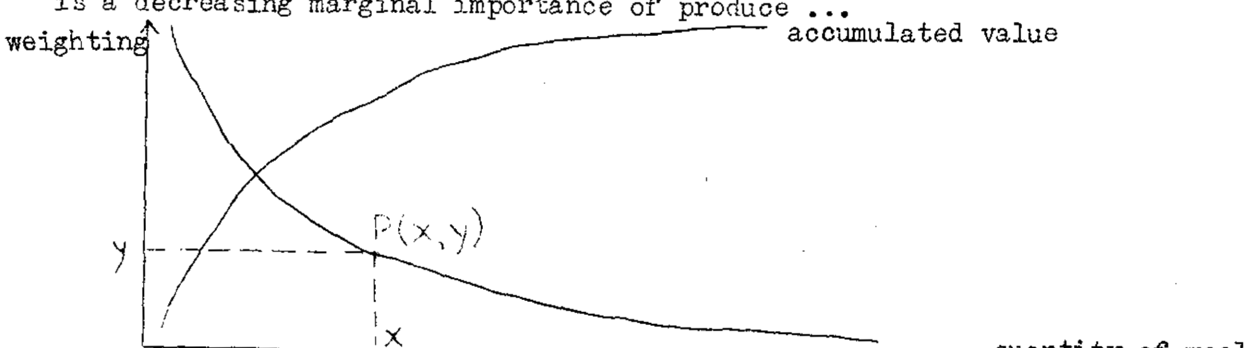
Most of the input-output coefficients are value independent, but not those of recreational potential. These depend on user preference and usage patterns. Variation in score arising from changing recreational preferences are not modelable since they cannot be predicted. But change arising from, for example, rising petrol costs causes recreation to be less car based and this change can be included in the scoring procedure and hence in the model.

Whether an output level is an objective on its own, part of some multiple objective, or simply a constraint, demand for it can be represented by a weighting versus quantity graph. If, for example, wool production is constrainted in the model to exceed x tonnes and it is also weighted at y $(0<y<1)$ in a multiple-objective function, then this can be represented by an infinite weighting for quantities of wool below x tonnes ...



The shape of the weighting curve for each commodity reflects the decision-makers' values.

It would be unusual for any one person, much less a community, to assign weightings to commodity outputs in the way shown above. Much more likely is a decreasing marginal importance of produce ...



with the point P(x,y) as simply one point on the weighting curve.

Use of a decreasing (linear and non-linear) weighting function would give a more realistic representation of the values of the community or the decision-maker. This might be quite accurately assessed for one person but community weightings of, particularly, ecological and recreational values could only be tentative. Provided the weightings could be reasonably described by a well defined function, a solution could be found to maximise the resulting non-linear objective function.

Unhappily for the modeller, values are not constant and so neither are weighting functions. Fowles (1977) analysed the problem of values in planning or future research generally and described the three strategies available for tackling this difficulty.

(i) Hazard guesses about future values. One should take account of the fact that future values may fluctuate and propose several different future value sets. These should be compared with the intended plan to see where problems might arise.

(ii) Consider altering future values. If resistance to a design for the future does not invoke deep-lying values, it may be a candidate for manipulation.

(iii) Create flexible plans. They should be constructed with as much opportunity for review as possible.

To proceed along these lines in generation and interpretation of model results would certainly add robustness to any conclusions drawn or plans implemented.

Table 6.1 Energy and labour in transportation

If the standard transport vehicle can carry 15 tonnes of product at 0.57 litre km^{-1} (5 miles per gallon deisel) with an average speed of 30 km hr^{-1} then ...

Energy cost of transport		=	1.7 MJ km^{-1} $tonne^{-1}$
	for timber	=	1.0 MJ km^{-1} m^{-3} (green Sitka Spruce)
	for milk	=	4.5 MJ km^{-1} GLU^{-1}
	for cattle	=	0.5 MJ km^{-1} GLU^{-1}
Labour cost of transport		=	0.00025 SMD km^{-1} $tonne^{-1}$
	for timber	=	0.00016 SMD km^{-1} m^{-3}
	for milk	=	0.00070 SMD km^{-1} GLU^{-1}
	for cattle	=	0.00007 SMD km^{-1} GLU^{-1}

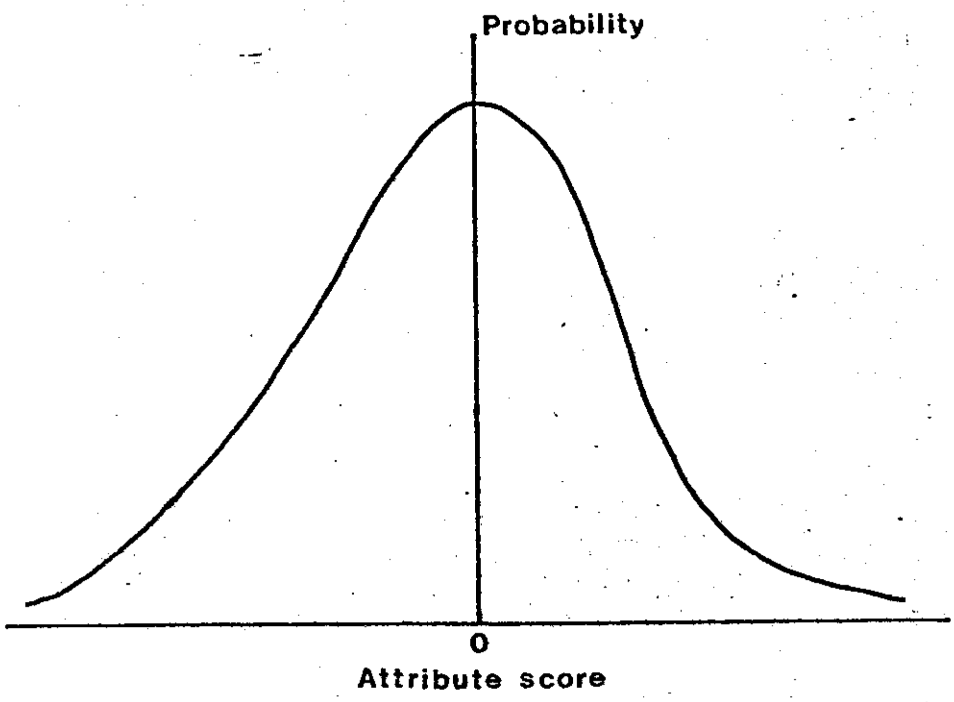


Fig 6.1 Probability distribution of score for one attribute in one land class.

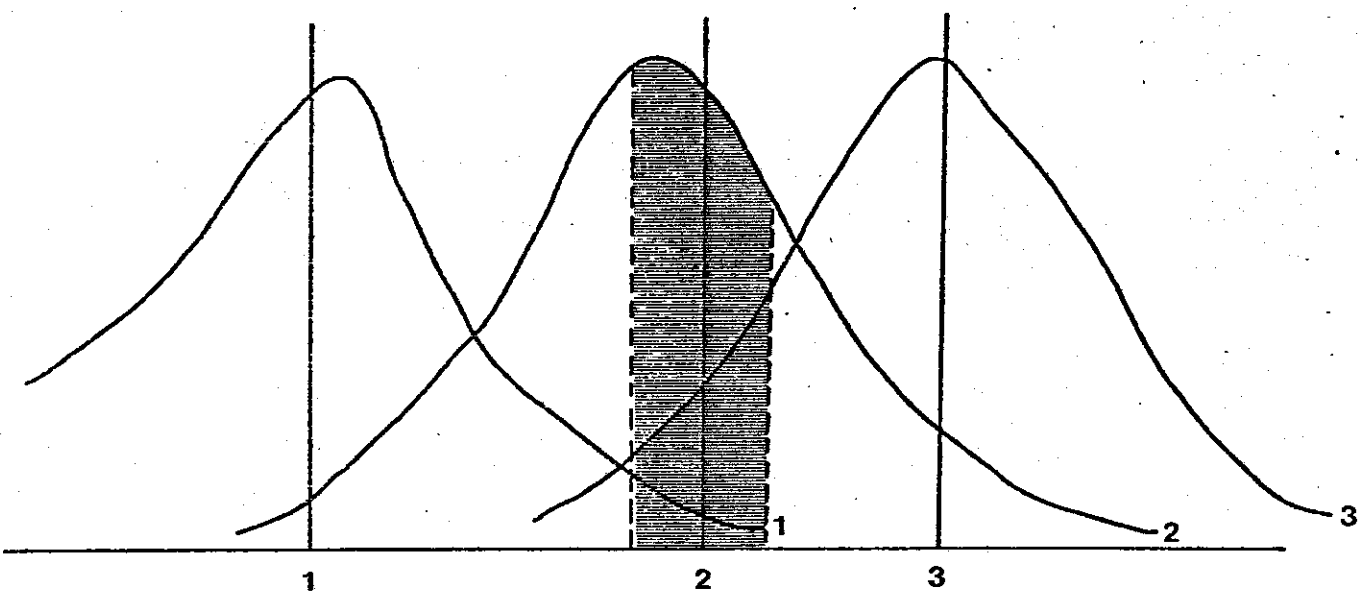


Fig 6.2 Probability distributions for three land classes.

If the model specifies class 2 for a particular use then the shaded land is most suitable even though it will come from all three classes.

6.2.1 SENSITIVITY ANALYSIS - THEORY

Single objective case

It is particularly important to know the sensitivity of the solutions of the LP problem to changes in the factor coefficients. Where there is uncertainty in the coefficients the extent to which this uncertainty affects the conclusions may throw doubt on the validity of the procedure.

Objective function

The simplest set of coefficients to check for sensitivity are those of the objective function. For non-basic decision variables a change in coefficient 'i' of θ_i will not change the basis provided it is less than a_{oi} - the i^{th} element of the last row of the solution tableau (as generated by the simplex algorithm). (These elements have no alternative physical interpretation.) For a basic decision variable the situation is slightly more complex and movement of the coefficient either up or down may alter the basis. The change θ_i must be such that

$$\max_j \left(-a_{oj}/a_{ij} \mid a_{ij} > 0\right) \leqslant \theta_i \leqslant \min_j \left(-a_{oj}/a_{ij} \mid a_{ij} < 0\right)$$

if the basis is not to change.

Constraint functions

In discussing the sensitivity of coefficients in the constraint functions it is assumed here that the constraints are minima. In other problems different directions of movement may be significant and the quoted formulae may have changes of sign.

The constraint function coefficients can be assessed with varying degrees of difficulty according to which of four possible situations is applicable to the particular coefficient.

(i) The coefficient relates to a non-basic variable and the corresponding surplus variable is basic (i.e. non-zero).

In this situation the coefficient does not affect the optimal solution at all. Thus, for example, if the optimal solution does not prescribe the use of any class 1 land for coniferous forest, and if timber production exceeds the constraint value, then the solution is insensitive to the volume of timber which class 1 is capable of producing. (This is of course not true if the objective is timber.)

(ii) The coefficient relates to a non-basic decision variable and the corresponding surplus variable is non-basic.

If the decision variable is x_i and the surplus variable y_i, and if the coefficient of x_i is increased by μ, then the optimal solution will be unchanged so long as

$$a_{oi} - \mu a_{oj} \leqslant 0$$

where a_{ok} is the k^{th} element of the bottom row of the tableau.

This method would apply if, in the situation above, the constraint on timber production was merely being reached, not exceeded. The element a_{ok} is the dual variable corresponding to the constraint in question.

(iii) The coefficient relates to a basic decision variable and a basic surplus variable.

Using the above nomenclature, the current optimal solution remains feasible if the coefficient is decreased by any amount less than y_i/x_i.

(iv) The coefficient relates to a basic decision variable and a non-basic surplus variable.

In this situation it is necessary to perform an additional pivoting operation creating a tableau with y_i in the basis and x_i out. This can give rise to computational complications but gives a measure of sensitivity from a combination of the original solution tableau and that newly created.

It may be that this more complex analysis can be avoided by making the constraint into the objective. For example, if the optimal solution includes the use of class 2 land for coniferous forest, and if the timber constraint is not exceeded then an adequate measure of sensitivity may be more easily achieved by making timber production the objective and testing using methods as given above.

Multi-objective case

In the multi-objective case where the coefficients of the objective function are an amalgam of the coefficients of the constraint functions two main problems arise in assessing sensitivity.

(i) A change in any coefficient will change both the corresponding constraint function and the objective function (unless the weighting is zero).

(ii) A change in one of the weightings used in constructing the objective function will change more than one of the elements of the objective function.

Thus, although sensitivity analysis on the objective function may still be readily performed, the results will not give any guide to the sensitivity of the results to the weightings and will give only an 'outer' limit of allowable change in coefficients.

Weightings

A change in the value of a factor weighting will change the objective function coefficient of all variables which may contribute to that factor. They will all change in the same proportion but this does not make calculation of the sensitivity to change any easier. If all the coefficients change by the same amount (as distinct from the same proportion) then a sensitivity is readily calculable. This situation is approximated if all the coefficients to which the weighting is applied are of similar magnitude (as least the same dimension) - for example, the recreational and ecological weightings could be tested under this approximation. Some conclusions might also be drawn in this way about the significance of change in the weightings of milk and timber production.

The change θ which is applied to all coefficients in set $\{i\}$ must be such that

$$\max_j \left(-a_{oj}/\textstyle\sum_i a_{ij} \,\middle|\, \sum_i a_{ij} > 0\right) \leqslant \theta \leqslant \min_j \left(-a_{oj}/\textstyle\sum_i a_{ij} \,\middle|\, \sum_i a_{ij} > 0\right)$$

if the basis is not to change. If this value is divided by a typical value of the coefficients involved a value for change in the weighting is obtained.

In cases where the range of the coefficients is greater or when a more accurate value is required the relevant test expression is $1 - a_{oj}/\sum_i c_i a_{ij}$ where $\{c_i\}$ are the objective function coefficients affected by the change in weighting. So if is the multiplicative factor the basis will be unchanged if

$$\theta \leqslant \min_j \left(1 - a_{oj}/\textstyle\sum_i c_i a_{ij}\right) \quad \text{for} \quad a_{oj} \leqslant \textstyle\sum_i c_i a_{ij}$$

or $$\theta \geqslant \max \left(1 - a_{oj}/\textstyle\sum_i c_i a_{ij}\right) \quad \text{for} \quad a_{oj} \geqslant \textstyle\sum_i c_i a_{ij}$$

Coefficients

An increase (decrease) in any coefficient will change the relevant constraint function and also produce (if the weighting is positive) an increase (decrease) in the corresponding objective function coefficient. Again we can consider four situations:-

(v) non-basic decision variable and basic surplus variable

The solution is not sensitive to change in the constraint function coefficient but the change in objective coefficient may be sufficient to bring the decision variable into the basis. This sensitivity will be accurately given by objective function analysis.

(vi) non-basic decision variable and non-basic surplus variable

Change in this coefficient may bring it into the basis through its effect on either the constraint or the objective function. If the constraint is a minimum, the weighting positive and the objective to maximise, then decrease of the coefficient will be unbounded while sensitivity to increase will be measured by the lesser of values given by objective function analysis and the rule in (ii) above (single-objective case). If the weighting is negative then only the sensitivity within the constraint function applies as the coefficient increases, and only the sensitivity within the objective function applies as the coefficient decreases.

(vii) basic decision variable and basic surplus variable

Again, if the constraint is a minimum and the object maximisation, then under either positive or negative weighting increase in the coefficient will be sensitive only within the objective function. Decrease in the coefficient could produce change in the optimum solution through either function and the lesser of the values given by objective function analysis and (iii) above will be the relevant measure.

(viii) basic decision variable and non-basic surplus variable

In this situation with either positive or negative weighting, increase or decrease of the coefficient may produce a change in the optimal solution through its position in both the constraint and objective functions. In each case the actual sensitivity will be the lesser of the sensitivity values arising from the two functions. The sensitivity as defined for the objective function will give an estimate of the allowed variation in the coefficient which is equal to or exceeding the true sensitivity. That is, the change in coefficient which will change the basis will be less than or equal to the value given in this way. Definition of the actual sensitivity will require computation as indicated in (iv) above.

Thus, in all situations of the multi-objective case, except in (vi) when the weighting is negative and the coefficient increasing, the sensitivity as given by objective function analysis is a maximum allowable change in coefficient. In other words, if such analysis indicates that the solution is highly sensitive to some coefficient then sensitive it is; if the method gives a low degree of sensitivity then the coefficient may still be significant through its influence on the constraint function.

6.2.2 SENSITIVITY ANALYSIS - APPLICATION

Sensitivity can only be strictly defined for a single solution to the LP problem. Each solution has its own set of sensitivities depending on the coefficients and constraints which define the problem.

On p. 90 the land uses which appeared in each class under present management and no land use restrictions for one or more objectives were listed. Certain of these would change class or be replaced by other uses through small variations in the coefficients. This is used as an example of the sort of review of results that sensitivity analysis allows ...

> In class 1, dairying appears under all objectives and is relatively insensitive. Beef and sheep however are only included in the basis under some objectives and may be removed by changes of less than 2% in a number of relevant coefficients in this or other land classes. Deciduous woodland would enter the basis under the ecological objective if its coefficient of ecological value were increased by 4%.
>
> All uses except beef and crops appear in the basis in class 2 under some objective. Beef would be recommended for maximum meat production through coefficient changes of < 0.1% and cropping would be included for food energy production if its output were up 1.7% relative to land class 6. Small reductions (< 1% for beef, < 5% for crops) in energy requirement would introduce these uses for energy conservation. Forest and woodland use appear only under the ecological objective and will be removed by changes of 2-4% in a number of ecological coefficients.
>
> Any of the livestock uses may appear under a number of objectives in class 3. Changes in coefficient greater than 20% are necessary to bring any other uses into the basis.
>
> All uses except cropping appear under some objective in class 4. A drop of 10% relative to class 8 is necessary to eliminate coniferous forest under the timber production objective; but a 2.4% increase in the recreational value of deciduous woodland in class 10 would remove this use from class 4 for this objective. Dairying is in the basis only for the food energy and labour objectives while beef is included under energy conservation and ecology. Otherwise the preferred use is sheep and is relatively insensitive to changes in coefficients.
>
> Class 5 is used exclusively for dairying unless the objective is energy conservation when beef is preferred in part of the area. The latter will also enter the basis through changes of < 0.3% in coefficients of meat production and recreational potential under these objectives.
>
> Only coniferous forest is not used under any objective in class 6. Dairy and sheep are the usual preference although cropping is preferred for food energy, labour requirement and energy

conservation. Beef is also recommended for the last objective. Cropping could be transferred to class 2 through relative changes of < 2% in labour requirement or food energy production. Deciduous woodland is recommended only for its ecological value while coniferous forest will enter the basis under this objective if the ecological value of the broadleaved woodland drops by 2.2% or if its own value increases 3.9%.

Coniferous forest is used in class 8 for energy conservation and will also appear under the timber objective with a 10% increase in productivity. Change in objective function coefficient of < 4% will bring deciduous woodland into the basis for energy conservation or ecological value. Otherwise beef, dairy and sheep are about equally preferred depending on the objective. Small changes in some coefficients will change the preference.

Class 9 is used for coniferous and/or deciduous forest under all objectives except energy saving when sheep are preferred. A small proportion is used for sheep on improved pasture under most other objectives. These results are insensitive to small coefficient changes except that beef could enter the basis with a 0.6% drop in its energy consumption, or a 5.3% increase in ecological value of improved beef land.

Improved grazing for sheep is the preferred land use in class 10 under all objectives except recreational potential and energy constraints. In the first unimproved grazing is preferred but increases of 2.4% in recreational potential of deciduous woodland or 4.4% in improved grazing land would bring them into the basis. All other uses are within small percentages of being in the basis under the energy objective, only deciduous woodland is not likely to be wholly removed. Drops of 10% or 5.3% in wool or meat productivity respectively would make the pasture improvement no longer preferred.

Class 11 shows a similar pattern with improved sheep land preferred under most objectives. Deciduous woodland is used for timber production and recreation and unimproved pasture for energy saving. Coniferous forest would be included for timber production with an 11% increase in output; beef for energy saving with a drop of 0.15% in consumption; a 7.0% fall in wool (or 3.6% fall in meat) productivity would make the pasture improvement not worthwhile.

Again improved pasture for sheep is the preferred use in class 12 unless the objective is energy saving. Then all other uses may appear with only coniferous forest almost certainly in the basis. Softwoods could also enter for timber production with a 9.3% productivity increase. The drops in wool or meat productivity which would make unimproved pasture preferable are 26% and 14% respectively.

The recreational (perhaps debatable) and ecological advantage of broadleaved scrub or woodland in class 13 makes this preferred use for all objectives except energy saving when beef is recommended. Coniferous forest will enter the basis for timber production with a 4.7% increase; 30% gains in meat production from improved sheep land, a 6% increase in ecological value, or 20% gains in recreational potential are necessary to replace the deciduous woods with sheep. Improved beef lands will enter with a 4.3% increase in ecological value.

Sheep grazing is the recommended use in class 14 for all objectives except energy saving (beef preferred) and ecological value (wilderness preferred). The results are insensitive to any changes in coefficient less than 15%.

Class 15 is very similar to 13. The same uses are preferred under the same objectives. Changes necessary to give other results are a 4.9% increase in coniferous forest timber production; a 4% increase in the ecological value of improved beef land (or 5.5% in improved sheep); a 15% gain in recreational potential of unimproved sheep grazing; or a 38% rise in meat productivity from improved sheep land.

Similarly, class 16 is similar to class 14 with sheep grazing recommended except where beef (energy saving) or wilderness (ecology) are preferred. A 14% drop in the recreational potential of the sheep relative to beef would bring in the latter use, as would a 17% increase in energy consumption. Beef will be preferred to wilderness if ecological values are 9% higher. The results are insensitive to other changes in coefficients.

An analysis of this kind in addition to indicating the degree of confidence that the decision-maker may have in the results can also aid in choosing the order in which various land use changes might be pursued. For example, while pasture improvement for sheep grazing is recommended under a number of objectives for classes 10, 11 and 12 this preference is least sensitive to coefficient changes in class 12 and so a beginning could be encouraged here with the greatest confidence.

Sensitivity levels, of course, change when the Parks and Common land use restrictions are imposed. In general, however, it is the choice of livestock in the lowland which is most sensitive to changes in coefficient. There is as much information available from the model on sensitivity as there are results and all the permutations cannot sensibly be discussed here. This resumé of the sensitivities associated with the objective function coefficients of one set of results is therefore only a guide. Obviously before any policy based on results of the model were contemplated a more detailed consideration of the sensitivity of the results being used would be necessary.

Such considerations, especially in conjunction with an assessment of potential errors (Sec. 4.3), would also indicate the members of the coefficient set which are most likely to disrupt conclusions and which therefore most need further research for better definition.

7. OTHER MODEL TYPES AND APPLICATIONS

There are a number of approaches to modelling besides linear programming which might be useful in land use planning in Cumbria. In choosing the type of model best suited to a particular problem a number of general points must be considered. These relate to:-

(i) the data requirements of the model and their availability;

(ii) the quantity and quality of information retrievable from the model; and

(iii) the ease of comprehension of the modelling process.

This last point is important. If decision-maker(s) are unable to understand what the model is doing, and why, they will be unwilling to act on any model recommendations which go against their own inclinations.

Dynamic programming

The dynamic programming method (Forrester, 1968) is fairly easily understood since it attempts to reproduce the important natural and human elements of the system under consideration. Involved are levels and rates within feedback loops all within a closed system. By setting these levels and assigning rates of change in accord with present conditions and policy the model should describe future trends. The effect on these trends of alternative policies can then be examined.

A simple dynamic model for rural Cumbria might take a form similar to the agricultural sectors of the World Model of Meadows et al. (1972). This would have to be adapted to include the recreational and ecological impact of land uses since these factors are particularly important in Cumbria.

A model of this type would require a large quantity of data since the links between model components (i.e. the rates) would not be the same in all land classes. Such data are not likely to be available in the near future.

More feasible is the use of dynamic modelling in a particular area with fewer options and more specific problems. The method has been used to better define the issues and to test policies in one Austrian valley (Bunnell et al., 1975) and could be similarly used in Cumbria where rising agricultural productivity coupled with inelastic demand and rising expectations is reducing community in some valleys to levels no longer viable.

Markov chaining

This also is essentially a descriptive approach to modelling. The difference between Markov chaining and dynamic program lies primarily in the data requirement and consequently in the reliability of results.

Instead of attempting to predict land use changes through the interactions of environmental parameters, change is assessed purely in terms of probability (Kemeny and Snell, 1960). Evidence of the past and knowledge of current policy are used to estimate the probability of change from one land use over a specified period.

In Cumbria, such a probability matrix might be derived for each land class.

Land class A

LAND USE (T+1 \ t)	S	H	B	D	C	L
S	0.95	0.10	0.10	0.02	-	0.12
H	0.01	0.80	0.04	0.04	-	0.03
B	0.02	0.04	0.60	0.02	-	0.25
D	-	0.02	0.04	0.65	0.15	0.05
C	-	-	0.02	0.25	0.85	0.05
L	0.02	0.04	0.20	0.02	-	0.50

In this example, between time 't' and time 't+1' (say 5 years later) there is a probability of 0.12 that land now being grazed by sheep will become coniferous forest. Since the basis of the Markov approach is no change in probability over time, the land use pattern at time 't+2' can be estimated by reapplication of the matrix. So the probability of change between "t" and "t+2" is found by squaring the initial matrix.

If a link could be established between planning policies and probability of land use changes, and if some desirable future land use pattern had been determined, then this method could be used in deriving policies which would produce the preferred land use pattern at a chosen time in the future.

Data requirements for a model (such as that suggested by Collins and Thomas (1973)) are quite low. The procedures are readily understandable. The quality of the results depends on the reliability of the data and the assumptions.

Input-output models

Input-output models are a type of linear model in that the inter-sector transfers of which they are composed are assumed to be independent of their own level or that of other transfers. In the most common type of economic input-output model these transfers are the monies paid by one industrial sector to another for intermediate goods, that is those goods not sold in response to final demand.

Recently such models have been extended to include inputs and outputs from and to the environment. These have been termed 'ecological commodities' by Victor (1972). In this way the effect of expansion of a certain industry or of demand for a particular commodity can be seen in terms of the additional movement of ecologic commodities.

Such analysis is extremely data consumptive and not particularly revealing if used in rural planning. Transfers between rural industries are generally small and there is little to be gained from the greater complexity of input-output models.

Should there be a trend toward more mixed use in rural areas and more material transfer between definable sectors then a material and energy, if not an economic, input-output model might prove useful for planning. The assumption of linearity, however, may prove a serious simplification in such an exercise. Also, there is no way that environmental 'services' such as landscape quality can be easily included in such modelling.

Dynamic linear programming

DLP is an extension of conventional linear programming to include time as a parameter. Following Propoi (1977) a problem concerning optimal rate of land-use change could be set up. For example, if a preferred mix of future commodity output were defined, and if some penality function directly related to rate of change were devised, then a "best" trajectory towards the "best" pattern of land use could be generated.

The objective function might be to minimise,

$$J(u) = \alpha'(T)\chi(T) + \sum_{t=o}^{T-i} (\alpha'(t)\chi(t) + \beta'(t)u(t))$$

where

$\chi(t)$ is the vector of difference in value of output at time t from the earlier defined optimal output vector

$u(t)$ is the vector of change in each land use in each time period (i.e. the decision variable)

$\alpha(t)$ and $\beta(t)$ are time dependent weightings on the deviation from potential output and the disfunction of change in land use.

T is the maximum time given for change to occur.

Constraints could be set on the time at which certain of the output levels must be achieved or on the degree of change in one output which must occur before another may be increased. The algorithm requires $u(t) \geqslant 0$ and so change cannot be considered as reversible.

Clearly, output of each factor and changes in land use are physically linked,

$$y(t) = G\,u(t) + y(0)$$

i.e. output at time t is equal to output at time t=o plus output generated by subsequent land use changes. Thus, difference between output at t and the optimal output is

$$\chi(t) = y(T) - y(0) - G\,u(t)$$

where $y(T)$ is the optimal output defined to occur at time T.

The factor G should define the output potential of each land use in each land class, and may also include factors to define the time lag between change in prescribed use and achievement of productive capacity. For example the gap between afforestation and timber production.

8. CONCLUSION

The successful use of linear programming for rural land use planning depends upon

(i) adequate definition of coefficients

(ii) procedures for contemplation of multiple objectives and changing value sets; and

(iii) a sound understanding in the decision-maker of the powers and limitations of the model.

Although more accurate estimates could conceivably be made for virtually all the coefficients of input and output used in the model there is little point in pushing such refinement. Distortion of reality introduced by the assumptions and omissions outlined in Sec. 6.1 makes the indiscriminate acceptance or use of results hazardous and the inaccuracies in numerical input need be reduced no further than the inadequacies of the theoretical procedures. In only a few cases is work clearly required on the former. These certainly include potential stocking rates in marginal uplands, high altitude forestry productivity and scoring of ecological values. If the existing land classes are too variable to permit better definition in these areas then further subdivision of classification may be necessary.

The physical area which was considered in this exercise was not a determining factor in the apparent usefulness of the work. Clearly the land classification scheme was vital. This same classification was based on the range of conditions in the whole of Cumbria and therefore a most useful basis for modelling the same area. A new classification would be necessary for areas which are considerably smaller - since the variation in land type would be reduced and more detail would be necessary to distinguish classes - or of very different complexion. However, provided a set of objectives can be defined, and provided the degree of achievement of these can be related to the nature of the land and the way it is used then modelling of this type can only increase insight into the implications of land use proposals.

Procedures exist for finding solutions most satisfactory to one decision-maker with multiple objectives (see Sec. 5.4). However, the land use pattern which best reflects the priorities of one individual now will not necessarily seem best to other decision-makers, to the public at large, or to anyone in the future. Therefore, solutions must be sought which seem most satisfactory not only in terms of a multiplicity of objectives, but also in terms of the range of weightings which may be applied to those objectives between the present and any time when a land use change becomes irrevocable. Zeleny (1974) describes procedures for finding all non-dominated solutions to a linear-programming problem. This set of solutions necessarily contains all possible preferred solutions whatever the weighting set implicit in a decision-maker's choice. With some knowledge of present values and possible future values (as modelled by, for example, Bossell and Hughes (1974)) some of the solutions can be safely eliminated from the nondominated set and policies may be available which do not immediately conflict with the remaining options. If it becomes necessary to select a particular solution (planning option) then this is a political decision and cannot be aided by mathematical objectivity. (Although Opensaw and Whitehead (1976) is of interest in **their** modelling of the decision process.)

During the work of which this report is a product there was considerable contact between the modeller and officers of the principal bodies concerned with land use in the county. Representatives of the County Council, the Lake District Special Planning Board, the Forestry Commission and the Ministry for Agriculture, Fisheries and Food (MAFF) met to discuss the method and the results as they appeared. This contact during model development gave those involved a greater degree of understanding of the benefits and limitations of mathematical modelling in general (and linear programming in particular), and provided a framework in which the often conflicting aims of the organisations could be discussed. However, the process of linking decision-makers and model was inhibited by

(i) the short period over which a complete model and the interested parties could be brought together;

(ii) the restricted computer facilities which made computational times long and therefore limited opportunities for 'playing' with the model; and

(iii) the necessarily part-time involvement of participants.

For modelling to be an effective aid to decision-making there must be considerable participation in model development and prompting from planning bodies. Then the model will be designed to fit the needs of the planners as closely as possible and the decision-makers will know sufficient of the model to sensibly question it, interpret its results, and know in what circumstances it can be trusted.

REFERENCES

A.D.A.S. and Agricultural Advancement Unit (University of Newcastle-Upon-Tyne), (1977). Financial results and measures of efficiency: Northern Region 1975-6, MAFF.

Bunnell, F., Bunnell, P., Buckingham, S., Hilborn, R., Margreiter, G., Moser, W. and Walters, C. (1975). The Obergurgl Model: a microcosm of economic growth in relation to limited ecological resources. Nature and Resources. 11, 10-21.

Benayoun, R., Larichev, O. I., de Montgolfier, J. and Tergry, J. (1971). Linear programming with multiple objective functions: STEP method (STEM), Mathematical Programming, 1:366-375.

Bocock, K. L. and Adamson, J. K. (1976). The effects of land-use and management on upland ecosystems, Merlewood Research and Development Paper No. 68.

Bossel, H. and Hughes, B. (1974). Simulation of value controlled decision-making approach and prototype, in Mesarovic and E. Pestel (eds), Multi Level Computer Model of World Development System, Proceedings of the Symposium held at IIASA, Laxenburg, 1974.

Bunce, R. G. H. and Smith, R. W. (1978). An ecological survey of Cumbria, Cumbria County Council (in press).

Busby, R. J. N. (1974). Forest site yield guide to upland Britain, Forestry Commission Record No. 97.

Capstick, M. (1972). Some aspects of the economic effects of tourism in the Westmorland Lake District, University of Lancaster, Dept. of Economics, unpublished.

Centre for Agricultural Strategy (CAS) (1976). Land for Agriculture, CAS Report 1, Reading.

Collins, H. A. and Thomas, A. R. (1973). A system study of the uplands of northern England and southern Scotland: Report of a pilot study, ISCOL Ltd., Lancaster.

Coomber, N. H. and Biswas, A. K. (1973). Evaluation of environmental intangibles, Genera Press, New York.

Dane, C. W., Meador, N. C. and White, J. B. (1977). Goal programming in land use planning, J. of Forestry, 75:325-329.

Edwards, A. and Rogers, A. (eds) (1974). Agricultural resources - an introduction to the farming industry in the United Kingdom, Faber, London.

Fanstone, G. H. and Himsworth, K. (1976). Choices for Cumbria, report of survey, Cumbria County Council and Lake District Special Planning Board.

Farming and Wildlife Advisory Group. The Dinas Conference on upland farming, forestry and wildlife conservation, 11, 12, 13 August 1972, MAFF.

Feist, M. J., Leat, P. M. K. and Wibberley, G. P. (1976). A study of the Hartsop Valley: a report to the Countryside Commission and the Lake District Special Planning Board, Countryside Commission Paper 92.

Forrester, J. W. (1968). Principles of Systems, Wright-Allen Press, Cambridge, Mass.

Fowles, J. (1977). The problem of values in future research, Futures, Aug. 1977, 303-314.

Goldsmith, F. B. (1975). The evaluation of ecological resources in the countryside for conservation purposes, Biol. Conserv. 9:89-96.

Green, B. M. (1977). Countryside planning: compromise or conflict? The Planner, May 1977, 67-69.

Heal, O. W. (1976). Upland Land Use: a desk study, interim report on Cumbria section, Institute of Terrestrial Ecology Project 398.

Helliwell, D. R., (1969). Valuation of wildlife resources, Regional Studies, 3:41-47.

H. M. Treasury, (1976). Rural depopulation, report by an inter-departmental group, HMSO, London.

Kemeny, J. G. and Snell, J. L. (1960). Finite Markov chains, D. Van Nestrand Co., New Jersey.

Leach, G. (1976). Energy and food production, IPC Science and Technology Press Ltd., Surrey.

Meadows, D. H., Meadows, D. L., Randers, J. and Behren, W. W. III (1972). The limits to growth: a report for The Club of Rome's project on the predicament of mankind, Pan Books, London.

Millar, A. (1964). Notes on the climate near the upper forest limit in the northern Pennines, Quat. J. of Forestry, 58:239-246.

Ministry for Agriculture (1966). Agricultural land classification, Agricultural Land Service, Tech. Report No. 11.

Nijkamp, R. and Rietveld, P. (1976). Multi-objective programming models: new ways in regional decision-making, Regional Science and Urban Economics 6:253-274.

Nix, J. (1976). Farm management pocketbook (7th Edition), Farm Business Unit, Wye College, London.

Openshaw, S. and Whitehead, P. T. (1976). Decision-making in local plans; the DOT methodology and a case study, Town Planning Review, 48:29-41.

Powell, L. B. (1971). Deteriorating Soil, in E. Goldsmith (ed), Can Britain survive? Tom Stacey, London.

Pritchard, N. M. and Anderson, A. J. B. (1971). Observations on the use of cluster analysis in botany with an ecological example, J. Ecol., 59:727-747.

Propoi, A. (1977). Dynamic linear programming models for livestock farms, IIASA RM-77-29.

Roberts, M. (1973). Increased production from Welsh mountain sheep by improvement of mountain pastures, Potassium Institute Ltd. Colloquium Proceedings No. 3.

Smith, D. M. and Johnson, E. W. (1977). Silviculture: highly energy efficient, J. of Forestry 75:208-210.

Trustrum, K., (1974). Linear Programming, Routledge & Kegan, London.

Van de Payne, C. (1975). Methods for linear and quadratic programming, North Holland.

Victor, P. A. (1972). Pollution: economics and environment. Allen & Unwin, London.

Waller, R. (1971). Prospects for British agriculture, in Can Britain Survive?, Tom Stacey, London.

Williams, M. R. W. (1975). Commercial tree-planting close to the upper altitudinal limits for timber production on the North Pennines, Quart. J. of Forestry, 69:219-221.

Zeleny, M. (1974). Linear multi-objective programming, Springer-Verlag, Berlin.

Zerbe, J. I. (1971). Forest products for a better environment. Forest Products Journal 21:16-18.

Appendix 1. Derivation of labour and energy requirements of agriculture (all labour figures from Nix (1976), energy figures from Leach (1976)).

A. Crops

Spring wheat - average UK per hectare per year

Activity	Man-hours	Use	GJ
Plough	3.3	Fertiliser (97 kg N	8.86
Seed bed cults	2.9	(48 kg P	
Seed & fertiliser	2.7	(48 kg K	
Top dress & roll	1.3	Fieldwork, tractors	3.24
Spray	0.7	Fieldwork, equipment	1.29
Harvest & store	4.4*	Spray (4 kg)	0.40
Later born work	0.9*	Drying, fuels	1.32*
Straw: bale	1.3	Drying, machinery	0.44*
cart	5.4*		15.6
	22.9		
		Bread making (4.2 tonnes)	70.1*
			85.7

Activities and uses marked * are considered to have input requirements proportional to the output of 44 GJ. Other inputs are considered as dependent only on the area being cropped.

Output dependent	1.34 SMD and 72 GJ
Output independent	1.53 SMD and 14 GJ

thus

labour (SMD) = 150 km^{-2} + 30 TJ^{-1}

and energy (TJ) = 1.4 km^{-2} + 1.6 TJ^{-1}

Potatoes (main crop) - average U.K. per hectare per year.

Activity	Man-hours	Use	GJ
Plough	3.3	Fertiliser (175 kg N	18.70
Seedbed cults	3.1	(175 kg P	
Fertiliser application	1.3	(250 kg K	
Seeding	18.0	Tractor, fuels, depreciation repairs	3.99
Hoe, harrow, mold up	7.8	Harvester, fuels, depreciation repairs	10.08*
Spray	2.7	Sprays (13 kg)	1.24
Burn off haulm	0.9	Seed shed fuels	1.57
Harvest, cart, clamp	118*	Storage	0.57*
Work on indoor clamp	6.7*		36.15
Riddle, bag, load	80*		
	242		

Output dependent 25.6 SMD and 10.65 GJ

Output independent 4.7 SMD and 25.50 GJ

Total output (food energy) 56 9 GJ

thus,

$$\text{labour (SMD)} = 470\ \text{km}^{-2} + 450\ \text{TJ}^{-1}$$

$$\text{energy (TJ)} = 2.6\ \text{km}^{-2} + 0.19\ \text{TJ}^{-1}$$

B. Livestock support land
- per hectare per year

	Man-hours		GJ
Arable - as for spring wheat			
	22.9		15.6
Leys- 3 year undersown			
Production	4.7	Fertiliser	10.68
Hay making	14.9	Fieldwork	2.0
	19.6		12.7
Improved pastures			
Production	4.7	Fertiliser	10.68
		Fieldwork	0.25
			10.93

	Man-hours		GJ
Permanent pastures			
Production	4.1	Fertiliser	7.48
		Fieldwork	0.25
			7.73
Rough grazing			
	nil		nil

Given the result in Table 3.

C. Stock

Dairy - per year

Milking cows	50 (42 to 60)	15.8
Replacement units	35.4	7.05
Calvesto 12 months	18	3.5
Calves to 2 years	10.8	3.5

Table 23(a) in the test gives the herd components of 1.68 GLU these require 75.9 man-hours and 20.8 GJ.

That is,

labour = 5.7 SMD per GLU

energy = 0.0124 TJ per GLU

Beef - per year

Beef cow requires just 12 man-hours and 8.5 GJ. Other units are as for dairy.

That is,

labour = 3.2 SMD per GLU

energy = 0.0087 TJ per GLU

Sheep - per year

(i) Labour - 4 man-hours per ewe (with lamb 6 months)
2 man-hours per hogg or 6-12 month lamb

lowlands - 2.4 SMD per GLU

uplands - 3.3 SMD per GLU

hill & fell - 4.1 SMD per GLU

from Table 24(a)

(ii) Energy - Leach gives no specific figures for energy usage in sheep farming. However, using his whole farm figures aand those already derived ...

(a) Average UK sheep farm
- per hectare per year

Total energy input 4.6 GJ

Outputs -	GJ	Implied inputs - GJ
Cereals	0.44	0.16
Roots	0.15	0.11
Milk & products	0.14	0.26
Cattle	0.21	1.50
Pigs	0.03	0.2
		2.2

If the land being grazed by sheep in rough grazing, then the energy input to sheep is 2.4 GJ.

Sheep output is 0.27 GJ, and taking land classes 13-16 as typical, this is the output of 0.31 GLU.

So, input for hill and fell sheep is 0.0077 TJ per GLU

(b) Average UK cattle and sheep farm
- per hectare per year

Total energy input 15.8 GJ

Outputs -	GJ	Implied inputs - GJ
Cereals	6.0	2.2
Roots	1.2	0.9
Milk & products	0.18	0.3
Cattle	1.35	9.6
Eggs	0.02	0.1
Pigs	0.08	0.4
		13.5

If sheep are rough grazed, then energy to sheep is 2.4 GJ. Sheep output is 0.46 GJ, and taking land classes 9-12 as typical, this is 0.39 GLU

So, input for upland sheep is 0.0059 TJ per GLU.

If for lowland sheep the energy requirement per GLU falls as the number of ewes per GLU then the input for lowland sheep is 0.0044 TJ per GLU.

D. Pasture improvement

Using Table B1 and the energy conversion of Leach (with energy costs slightly increased to approximate 1972/3 prices) the inputs to pasture improvement are ...

Fertiliser £1200 at 500 MJ/£	...	0.60 TJ
Power (fuels) £600 at 2600 MJ/£	...	1.56 TJ
Machinery £140 at 150 MJ/£	...	0.02 TJ
Sundries £240 at 100 MJ/£ (?)	...	0.02 TJ
1 extra man		300 SMD

This is, when spread over the 8.43 km^2 property, 0.26 TJ km^{-2} and 35 SMD km^{-2}. Increased output is represented by

800 extra ewes	...	160 GLU
20 extra beef cows	...	29 GLU

That is, 22 GLU km^{-2}. There is additional labour and energy involved in keeping these additional 22 GLU. So, for example, on land devoted entirely to sheep in land classes 9-12 the budget would be ...

Inputs:

Labour	35 + 22 x 3.3 = 108 SMD
Energy	0.26 + 22 x .0059 = 0.39 TJ

Outputs:

Meat	22 x .092 = 2.0 tonnes
Wool	22 x .0116 = 0.26 tonnes
Food energy	22 x .00118 = 0.026 TJ

The other figures of Table 4.38 are derived in the same way.

Pasture improvement budget

(from Roberts, 1973)

Pasture improvement	£.p.
3 tons per acre ground limestone plus spreading	6.45
15 cwts per acre mini granular slag plus spreading	6.75
Fertiliser: 94 uts N, 30 uts P_2O_5, 30 uts K_2O per acre + spreading	6.25
Seeds plus sowing	3.85
Flail mowing	1.60
Surface rotavation	0.60
Rolling	0.40
	25.90
Fencing per acre	1.05
Access roads	2.40
Total cost per acre	29.35

300 acres at £29.35 per acre	£8,805.00
Cost of rearing 800 ewes	£4,000.00

Loss in income over four years when building stock numbers would be £1,000 per annum. To counteract this, there is £8,000 capital available through the sale of 400 acres to the Forestry Commission at £20.00 per acre, which in a grant aided scheme would be sufficient to cover the cost of pasture improvement and investment in extra stock.

Additional annual charges involved as a result of improving 300 acres of rough grazing

	£
Annual fertiliser cost at £4 per acre	1,200
Power and machinery at £2.47 per acre	741
Annual charge on building to house 20 cows	220
Sundries at £0.82 per acre	246
1 extra man	1,200
	3,607
Extra gross margin on 800 ewes at £5.00	4,000
Extra gross margin on 20 cows at £63.00	1,260
Total extra gross margin	5,260
Extra costs	3,607
Increased net income	£1,653

Appendix 2. Prices and values

Some monetary, and often market, value can be given to each factor in the model. In some cases (timber, energy, labour) the level of supply or use in Cumbria will not seriously affect prices. In others however, (e.g. food energy, recreational potential) the price or value is much more sensitive to supply and the use of one value over the possible output range is inappropriate. Values given here are only intended for example and, although most will be roughly correct for present output levels, they should not be used to draw any conclusions about costs or opportunities in Cumbria.

1. Timber

Average prices for standing softwood were £7.864 m^{-3} in 1974-5 and £5.794 m^{-3} in 1975-6. A figure of £7 m^{-3} is used here.

2. Meat

Nix (1976) gives prices to farmers as £0.54 kg^{-1} for beef and £0.90 kg^{-1} for lamb. In view of the existing production patterns an overall price of £620 $tonne^{-1}$ is reasonable. This is about £300 $tonne^{-1}$ net of food energy value (see below).

3. Food energy

Leach (1976) rates beef at 10.17 MJ kg^{-1} and lamb at 12.81 MJ kg^{-1}. The implied food energy prices are therefore

Beef £53 GJ^{-1}

Lamb £70 GJ^{-1}

Similarly,

Milk - 2.72 MJ kg^{-1}	and 9.65p litre	£35 GJ^{-1}
Potatoes- 3.18 MJ kg^{-1}	and 10p kg^{-1}	£31 GJ^{-1}
Bread - 10.6 MJ kg^{-1}	and 20p kg^{-1}	£19 GJ^{-1}

Other vegetables are much more expensive as food, e.g. peas £170 GJ^{-1}, carrots £200 GJ^{-1} and winter lettuce £5000 GJ^{-1}.

If a basic value of £30 GJ^{-1} is assigned to food energy, then the remaining cost of meat is £30 GJ^{-1} or £300 $tonne^{-1}$ and of milk £5 GJ^{-1} or £14 $tonne^{-1}$.

4 and 5. Recreational potential and ecological value

No market prices exist for these commodities. Various valuation schemes exist (for example Coomber and Biswas (1973), Helliwell (1969)) but these are generally site specific and based on assumptions that do not hold over an inhomogeneous area the size of Cumbria.

The English Tourist Board has estimated that Cumbria makes £50-60 million from tourism annually (see also Capstiok, 1972). This is about £150 per recreational potential unit. Clearly this is not entirely generated by the rural study area and since the county is presently oversupplied additional units will certainly not have this value.

There is some overlap (double counting?) between recreational potential and ecological value. An area of high nature conservation value will draw tourists and separation of factors is not easy. National Park Policy is to give nature conservation a higher priority than provision of recreation.

The two factors have similar county wide totals (under present use) and so first approximation values are taken as £20 and £25 per unit for recreational potential and ecological value respectively.

6. Energy

For 1970-1 Leach (1976) estimated costs as ...

Fertiliser	£1.9 GJ^{-1}
Fuels	£0.38 GJ^{-1}
Electricity	£0.60 GJ^{-1}

The steep increase in oil prices since 1973 make these unsuitable for comparison with the more recent prices of other commodities. At 60p per gallon and 80% conversion efficiency fuel is about £3.0 GJ^{-1} while electricity at 2p per kWH and 25% efficiency is £1.4 GJ^{-1}. With fertiliser clearly having a higher cost the others and being a large part of the rural energy budget a cost of £4 GJ^{-1} is taken as a mean.

7. Labour

A net cost of about £8 SMD^{-1} (or £2000 man-year^{-1}). The value associated with created jobs is harder to assess. Some figures on costs and benefits of job creation are given in the 1976 H.M. Treasury report 'Rural Depopulation' but the complex of employment, subsidy, social welfare and resource considerations makes distillation to one figure impossible.

8. Milk

A value of £14 tonne^{-1} net of food energy value (see above).

9. Wool

The 1976-7 support price was 83.8p kg^{-1} or £840 tonne^{-1}.

These prices, values and costs can be used as a weighting scale for creation of a multi-objective function ...

	Value (£)	Weighting
Timber (m^{-3})	7	0.00020
Meat (tonne x^{-1}	300	0.00852
Food energy (TJ x^{-1}	30,000	0.85230
Recreational potential	20	0.00057
Energy consumption (TJ x^{-1}	4,000	0.11364
Ecological value	25	0.00071
Labour (SMD x^{-1}	-8	-0.00023
Milk (tonne x^{-1}	14	0.00043
Wool (tonne x^{-1}	840	0.02386

This gives each unit of this multi-objective function a value of approximately £35,000. The implied value of the final solution of Table 5.9 is £0.13 x 10^9. However, this solution includes a 50% increase in food energy production all of which may not be marketable at the price given.

In a similar way, the possible county output levels with and without the National Parks can be compared. If the same constraints and weightings which gave the final solution of Table 5.9 are applied to the county without the Parks and Commons land use restrictions, then under the given prices the output is with £0.10 x 10^9 mainly in extra food energy production, but also in higher ecological value.