VARIABILITY OF HERBAGE VARIETIES

by

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DECLARATION

The following record of research work is submitted as a thesis for the degree of Master of Philosophy in the University of Edinburgh, having been submitted for no other degree. Except where acknowledgement is made, the work is original.

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ABSTRACT

Statistical techniques concerned with variability in the performance of treatments in a series of agricultural crop experiments are reviewed with particular reference to the problems associated with a multiple harvest crop.

Before seed of a new crop variety can be sold in the United Kingdom, it must be shown to give some improvement in value beyond that available from existing varieties. Since 1974 the value of new crop varieties has been assessed in a nationally organised series of field trials.

In this thesis yield data from five years of national trials with varieties from four herbage and one herbage legume species are examined to assess the extent to which varieties vary in their performance over sites and seasons. The effects of variability on the making of decisions on the future of new varieties and on the allocation of trial resources are considered. Methods for the statistical control of within-trial variability in herbage sward field work are reviewed.

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CHAPTER 1

INTRODUCTION

1.1 FOREWORD

It is a characteristic of experimental work in many areas that the effects of treatments vary when repeated. The control, measurement and partitioning of experimental variability is the primary role of statistical methodology in scientific research.

In agricultural experiments, treatments are usually replicated within a site. The treatments are often applied at several sites and repeated over several years. In this thesis, one area of agricultural experimentation is considered, the testing of varieties of herbage and herbage legume crops to estimate their future yield performance.

A feature which distinguishes herbage from many other crops is its harvesting which extends for some years after sowing. In each harvest year the produce is cut several times during the season. The analysis of data from multiple harvests poses several statistical questions. Some of these questions are examined in the thesis.

While our primary concern here is with the routine estimation of relative variety performance, nevertheless the problems of variety testing are sufficiently general for this work to be of some relevance in any area where treatments are evaluated on a multiple-harvest crop.

1.2 HERBAGE VARIETY TRIALS

1.2.1 Crop variety testing in UK

In the UK, new agricultural crop varieties for the farmer come from private plant breeders or state plant breeding stations within the UK, or are introduced from abroad.

Independent testing of new varieties is the responsibility of a number of organisations (England and Wales: National Institute of Agricultural Botany (NIAB); Scotland: Scottish Agricultural Colleges and the Department of Agriculture for Scotland; Northern Ireland: Department of Agriculture in N. Ireland).

Two stages of testing operate. At the first stage a variety's suitability for inclusion in the UK National List (NL) is assessed. In the UK, sale of seed of agricultural crop varieties is restricted by statute to those varieties named in the NL or in the European Community's Common Catalogue (a European List). To be entered in the NL a variety must be shown to represent a clear improvement in cultivation and use over listed varieties. It must also be distinct from other varieties, uniform in its plants, and stable with regard to its reproduction. The object of the first of these requirements is to maintain and improve the general performance standards of varieties. The purpose of the second requirement is to encourage the development of new varieties by protecting the commercial rights of the plant breeder.

At the second stage, the best varieties from the NL stage are selected by the testing authorities and grown in a greatly extended range of seasons and centres, and are subsequently considered for inclusion in a Recommended List (RL). A separate RL is published annually for each of the principal crop species. Each RL contains details of varieties currently recommended for growng by farmers together with estimates of their expected performance relative to established varieties, based on trials data and other experience.

The NL and RL stages are closely linked. The same testing organisations are responsible for both stages and the results of NL trials are used for RL purposes. The two stages differ in a number of important aspects. The NL system has operated only since 1974 but the RL has been in existence for very much longer. There is a single NL for the UK while separate RLs are published in the three parts of the UK. The RL promotes the better varieties and the NL excludes the weaker. Once entered on the NL a variety may remain there at the discretion of the breeder while a RL is reviewed annually and removal from the List can occur at any time depending on performance in trials relative to other varieties.

This thesis is concerned with NL and RL testing for performance in cultivation and use. Testing for distinctness, uniformity and stability is not considered.

1.2.2 Herbage variety testing

Official UK performance trials are done of varieties from ten herbage species. Five of the more important of these species are the subject of this thesis:

Herbage (Grass)	- Perennial ryegrass	(PRG)
	- Italian ryegrass	(IRG)
	- Timothy	(TIM)
	- Cocksfoot	(CFT)
Herbage legume (clover)	- Red clover	(RCL)

In 1980, of the 360 varieties of all species in NL trials, 189 were herbage species and 159 came from these five species.

Every year, separate field trials of each species are sown at between seven and eleven centres. The distribution of species between centres is shown in Table 1.1. Their location is indicated on the map in Figure 1.1.

The centres are experimental farms and the same farms are used each year. While the centres are fixed the location of the trials within the centre can vary from year-to-year.

The number of centres at which a species is sown broadly reflects the relative importance of that species. The allocation of a species to a centre is partly determined by interest in the species in the region; it is also influenced by operational factors such as the willingness and ability of a centre to operate the trial.

Harvesting of trials commences in the year after sowing and continues for two years. Thus at each centre there are three sowings of the same species in the ground at any one time - trials sown in the present year, in the previous year and two years ago.

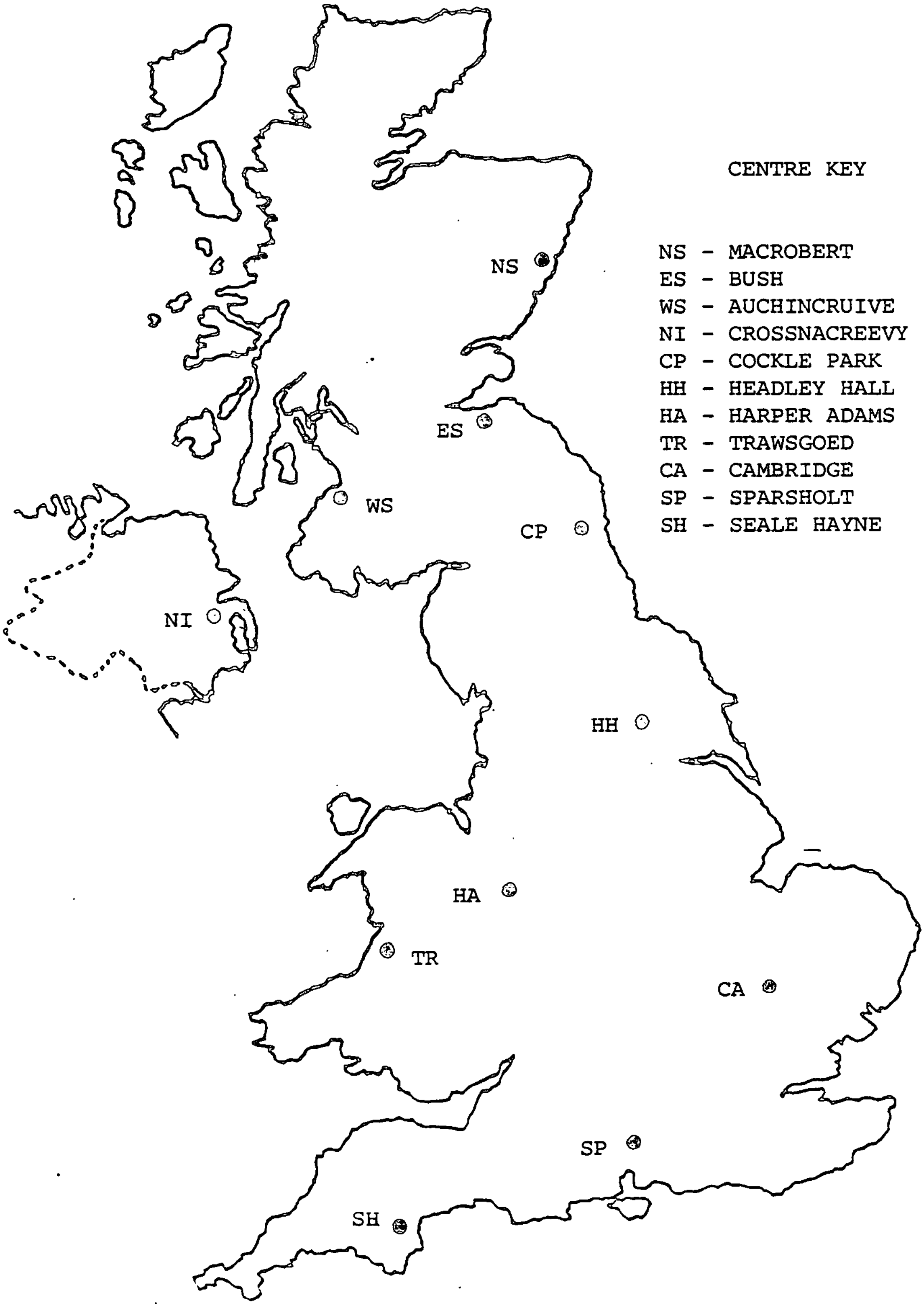
1.2.3 Experimental treatments

In trials of each grass species four plots of every variety are sown. The plots are paired and pairs are treated separately: a frequent cutting system is applied to one pair of plots which are harvested at nine intervals of 4 weeks during the growing season; a conservation cutting system is applied to the other pair of plots which are cut at four intervals between June and October. Frequent cutting management simulates pasture conditions grazed by

Table 1.1: Trial centres for herbage species

	CENTRE	CENTRE CODE	PERENNIAL RYEGRASS	ITALIAN RYEGRASS	TIMOTHY	COCKSFOOT	RED CLOVER
				Species sown at centre (*)			
ENGLAND & WALES	Seale-Hayne, Devon	SH	*	*	*	*	*
	Sparsholt, Hampshire	SP	*	*			*
	Cambridge	CA	*	*	*	*	*
	Harper Adams, Salop	HA	*	*			
	Trawsgoed, Dyfed	TR	*	*	*	*	*
	Headley Hall, Yorks.	HH	*	*			
	Cockle Park, Northumberland	CP	*	*	*	*	*
SCOTLAND	Auchincruive, Ayr	WS	*	*	*		*
	Bush, Midlothian	ES	*	*	*	*	*
	Macrobert, Aberdeenshire	NS	*	*	*	*	*
N. IRELAND	Crossnacreevy, Belfast	NI	*	*	*	*	*
	NO. OF CENTRES		11	11	8	7	9

Figure 1.1: Distribution of herbage variety testing centres



animals while conservation cutting represents a system in which grass is cut for feeding to animals.

In the red clover trials there are three plots of each variety and a common conservation cutting system is applied to all plots.

New varieties are sown in two consecutive years. In each trial there are also sown several established varieties (called controls) against which the new varieties will be compared. Thus a trial will include varieties in their first and second sowing years, as well as controls.

1.2.4 Trial design

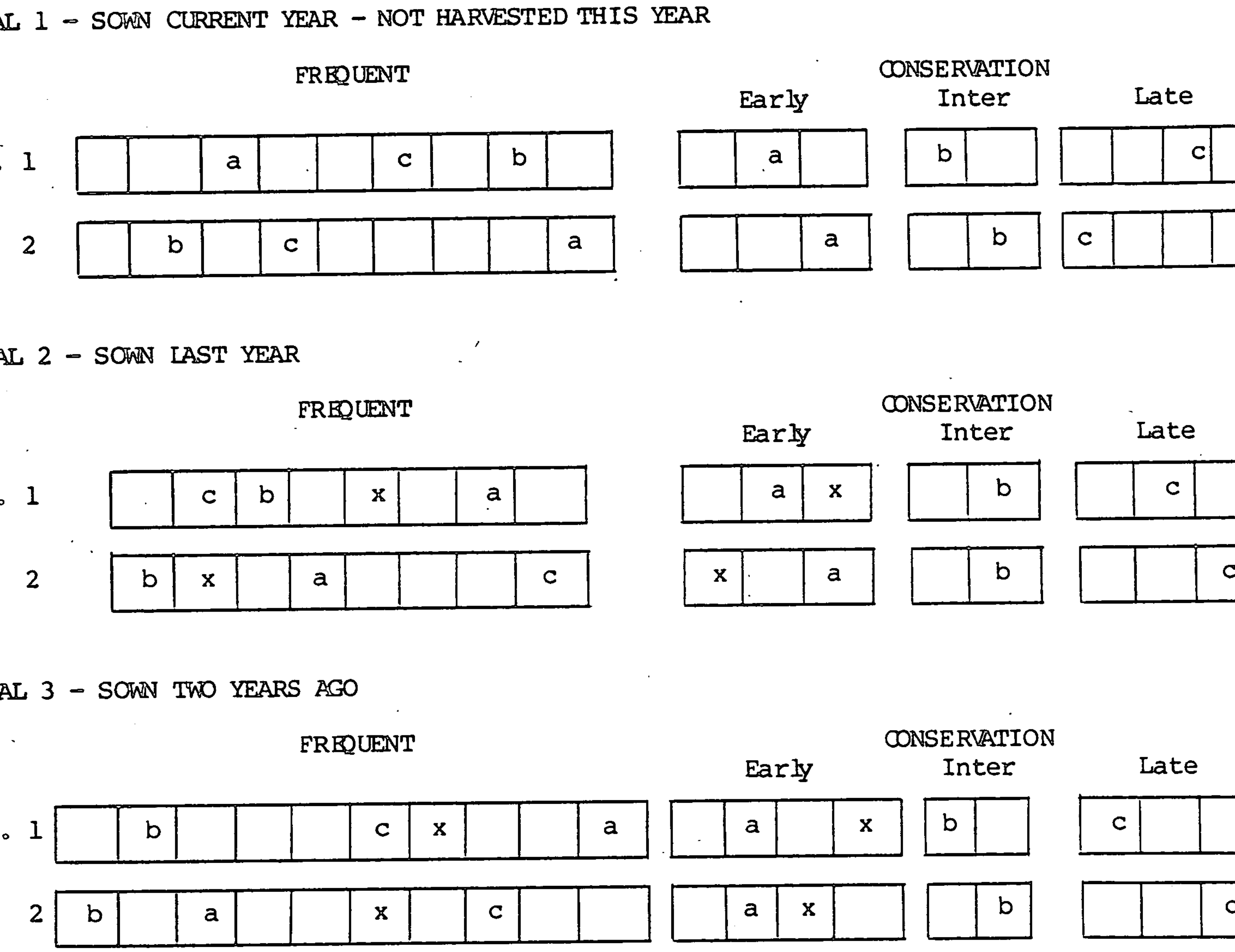
In conservation management, to facilitate cutting at different starting dates, varieties are grouped by maturity (5 groups in PRG, 3 in IRG and TIM, 2 in CFT and RCL) and different maturity groups are tested in separate trials. In the frequent cutting system, all maturity groups are cut together and varieties are sown and results analysed as a single trial.

Figure 1.2 illustrates the arrangement of trials for one species at a centre. The photograph in Figure 1.3a shows the plots at one centre (ES).

Randomised complete block arrangements were used to assign varieties to plots in all but one of the trials considered here; the one exception was sown as an incomplete block design.

Randomised field layouts are produced using the CVT computer program (Talbot and Robinson, 1980). Varieties are assigned at random to plots within blocks and blocks randomised amongst each other. A copy of the layout (Figure 1.4) is stored on the computer for use in later analysis.

Figure 1.2: Typical arrangement of trials for one species at a centre



NOTE: Boxes represent plots and letters in boxes identify varieties.

Varieties a, b and c are early, intermediate and late maturity group controls respectively which are sown each year in each trial

Variety x is a new early variety sown for first time two years ago in trial 3 and sown for second time last year in trial 2.

Figure 1.3a: Herbage variety trial plots at ES centre

Figure 1.3b: Plot harvester

Figure 1.4: Example of herbage variety trial layout

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✩✩✩✩ NATIONAL/RECOMMENDED LIST VARIETY TRIALS ✩✩✩✩
                                                                        T    78   ES   5   CE   BUSH

   DESIGN TYPE          PLOTS  SUPERBLOCKS  VARIETIES  PLOTS/VARIETY

COMPLETE BLOCK            14          2           7            2

    CODE      VARIETY                 PLT  SUP  VTY       PLT  SUP  VTY

     1       S352                      1    1    5          8    2    5
     2       ERECTA RVP                2    1    2          9    2    2
     3       MELORA                    3    1    6         10    2   11
     4       POTA                      4    1   11         11    2    4
     5       DP14/E/69                 5    1    1         12    2    3
     6       ZW42/79                   6    1    3         13    2    6
    11       EMMA                      7    1    4         14    2    1

RANDOMISATION SEEDS -                ✩

DATE OF SOWING -
```

1.2.5 Trial husbandry

Seed for the trials is supplied by the breeder or the breeder's agent in separate submissions for each sowing year. Certified seed is requested but it is not possible to ensure that this is what is supplied. The seed is divided at the NIAB and sent to each of the centres. At a centre the seed is sub-divided for sowing in separate blocks.

Trials are sown from late spring to early autumn depending on species and location of centre. A common seed rate is used for all varieties within the same ploidy group but tetraploid varieties are sown at a rate 1.5 times that of diploid varieties. Within a block each variety is drilled into a plot of size approximately 5m by 2m with the long sides of plots abutting other plots in the same block.

In the establishment year, fertiliser and weed control is applied as required and at the discretion of the centre. In the years of harvest, fertiliser is applied at fixed rates of nitrogen in stages throughout the year. No chemical weed control is used during harvest years. Other husbandry operations follow good local practice.

Scheduled dates of cutting in the harvest years are given in Table 1.2. Early and late frequent cuts are not taken at some centres. Apart from this, and despite adjustments for weekends, holidays and wet weather, no substantial departures from the schedule have been noted.

Plots are harvested with a grass mower which cuts a 1 m strip through the centre of each plot at a height of 3 cms for frequent

Table 1.2: Cutting schedule for herbage trials

	CUT NO.	TIMING	CUT GROUP
FREQUENT			
	1	10 April	1
	2	1 May	
	3	21 May	2
	4	10 June	
	5	1 July	
	6	1 August	3
	7	1 September	
	8	1 October	4
	9	1 November	
CONSERVATION			
	1	Fixed number of days from 50% heading of standard variety (50% flowering for RCL)	1
	2	6 weeks after cut 1 (4 weeks after for IRG and CFT)	2
	3	6 weeks after cut 2 (4 weeks after for IRG and CFT; 8 weeks after for RCL	3
	4	Aftermath cuts taken as necessary in September and October	4

cuts and 6 cms for conservation cuts. The cut grass is raked off for weighing. Fresh yields are recorded to the nearest .1 kg. At some centres, in recent years, a harvester has been used which cuts, collects and automatically weighs the fresh yields (Figure 1.3b).

From each plot a 300 gm sample of cut grass is taken for drying and assessment of the dry matter content.

1.3 COLLECTION OF DATA

1.3.1 Data recording

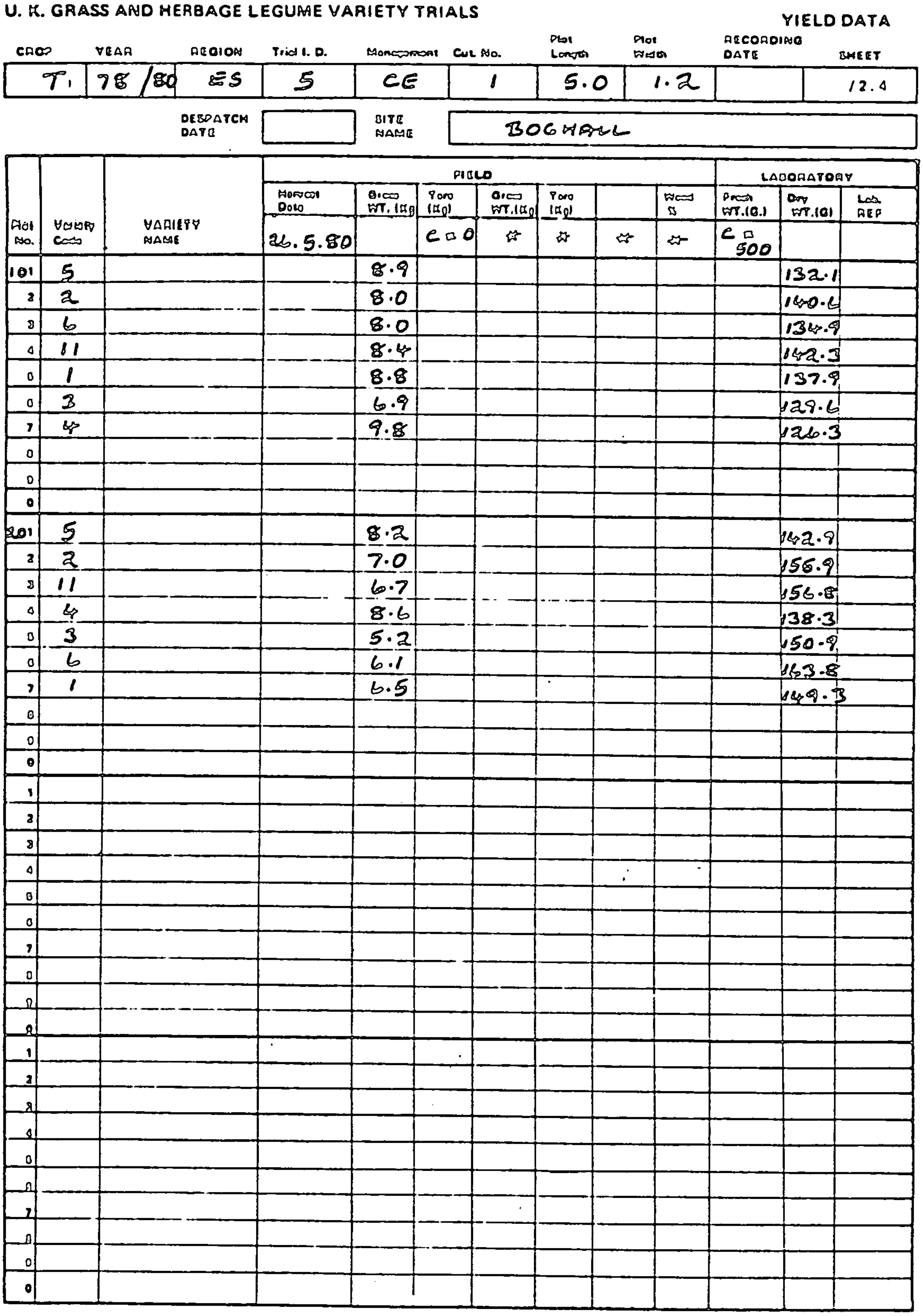
Records are made directly on to specially designed recording sheets which give two-part copies (Figure 1.5). A copy is sent to a computer centre at NIAB, Cambridge; ARC Unit of Statistics, Edinburgh; or Biometrics Division DANI, Belfast, as appropriate. There the data are punched for entry to the computer and punched again for verification. The CVT computer program is used to read and derandomise the data; derive individual plot dry matter (DM) yields from the harvested fresh yield and DM content assessments; analyse plot DM yields; print and store summaries. A copy of the summary for each cut is sent for checking to the officer responsible for the trial (Figure 1.6).

In late autumn of the first and second harvest years the percentage persistence of the sown species in the plots subject to frequent cutting is assessed. In each trial the plots with the highest and lowest persistence are identified and the persistence estimated by plant counts. All of the plots are then scored on a 0-9 scale and the persistence of individual plots estimated by linear calibration of their score with the scores and persistence percentages of the best and worst plots. These data are processed and stored on the computer as for yield observations.

Assessments of establishment, winter damage, disease susceptibility, and the quality of the harvested crop are also made but these are not considered in detail here.

Data on site characteristics - soil type, climate - are also recorded.

Figure 1.5: Example of herbage variety yield record sheet



U. K. GRASS AND HERBAGE LEGUME VARIETY TRIALS

YIELD DATA

CROP	YEAR	REGION	Trial I. D.	Management	Cut No.	Plot Length	Plot Width	RECORDING DATE	SHEET
T1	78 /80	ES	5	CE	1	5.0	1.2		12.4

DESPATCH DATE ☐ SITE NAME BOGHALL

			FIELD							LABORATORY		
Plot No.	Variety Code	VARIETY NAME	Harvest Date	Green WT. (Kg)	Tare (Kg)	Green WT. (Kg)	Tare (Kg)		Weed %	Fresh WT. (G.)	Dry WT. (G)	Lab. REF
			26.5.80		C □ 0	☆	☆	☆	☆	C □ 500		
101	5			8.9							132.1	
2	2			8.0							140.6	
3	6			8.0							134.9	
4	11			8.4							142.3	
5	1			8.8							137.9	
6	3			6.9							129.6	
7	4			9.8							126.3	
8												
9												
0												
201	5			8.2							142.9	
2	2			7.0							156.9	
3	11			6.7							156.8	
4	4			8.6							138.3	
5	3			5.2							150.9	
6	6			6.1							163.8	
7	1			6.5							149.3	
8												
9												
0												
1												
2												
3												
4												
5												
6												
7												
8												
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0												
1												
2												
3												
4												
5												
6												
7												
8												
9												
0												

Figure 1.6: Results from analysis of one harvest

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                                                                                          24.31
☆☆☆☆ NATIONAL/RECOMMENDED LIST VARIETY TRIALS ☆☆☆☆

                                                     T     78   80   ES    5    CE   BUSH

   MEASURE - DRY MATTER YIELD (MT/HA) FOR CUT  1
                                                                         CUTTING DATE -    26.5.80

                          PLOT DATA
VARIETY             MEAN                 WEED P/C                 ☆

S352                3.64    4.05   3.23          ☆        ☆
ERECTA RVP          3.69    3.75   3.64
MELORA              2.80    2.98   2.62
POTA                4.05    4.13   3.96
DP14/E/69           3.91    3.92   3.91
ZW42/79             3.46    3.60   3.33
EMMA                3.74    3.98   3.50

    TRIAL MEAN      3.61

       SE          0.135

  VARIETY F SIG      1.0

      LSD          0.466

   CV PERCENT        5.3


ESTIMATE OF MV -          ☆
```

1.3.2 Data validation

The main responsibility for checking trial results lies with the trials officer. However a routine check is applied to the results of the analysis of individual cut yields by which a coefficient of variation (CV) that exceeds 15% is treated as a warning to check the data. In practice, it has been found that variability is not well related to level of yield from individual cuts and the CV criterion is not applied rigorously.

1.3.3 Combining cut yield data

At the end of a season, frequent cut plot yield data are summed over cuts into four cut groups as indicated in Table 1.2. Total season yields are also calculated for both frequent and conservation management. All cut totals are then summarised by calculating variety means and standard errors (Figure 1.7).

Figure 1.7: Example of over-cuts summary analysis for yield from one trial

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**** NATIONAL/RECOMMENDED LIST VARIETY TRIALS ****

                                                     T     78   80   ES    5     CE    BUSH

         MEASURE - DRY MATTER YIELD (MT/HA)

                               CUTS
GP C1 C2  VARIETY           -1     2      3      4      TOTAL   OVER YRS   P/C1  P/C2

2  0  1  S352              3.64   4.22   5.03   0.32    13.21     12.59    100   100
2  1  0  ERECTA RVP        3.69   4.72   5.43   0.39    14.23     12.64    100   100
2  0  0  MELORA            2.80   5.52   4.45   0.22    12.99     11.85     94    94
2  0  0  POTA              4.05   4.36   4.65   0.36    13.42     12.35     98    98
2  0  0  DP14/E/69         3.91   4.30   5.06   0.34    13.62     12.56     99   100
2  0  0  ZW42/79           3.46   5.16   4.78   0.28    13.68     11.92     94    95
2  0  0  EMMA              3.74   4.74   4.61   0.34    13.43     12.59    100   100


         TRIAL MEAN        3.61   4.72   4.86   0.32    13.51     12.36

            SE            0.135  0.310  0.175  0.031    0.267     0.250

           LSD            0.466  1.071  0.606  0.108    0.923     0.865
```

1.4 USE OF DATA

1.4.1 Stages of testing

Every candidate variety for the NL is sown at all centres in two sowing years along with control varieties. When the results of both harvest years are available - generally four years after first sowing - the new variety is considered for inclusion on the NL.

If the variety is accepted on to the NL, it can be considered for inclusion on the RL, usually without further trials being done. This procedure differs from that for some other crop species where testing beyond the NL stage is required.

Once fully recommended, a variety is not re-tested in main trials for several years. The large number of varieties involved and the need to harvest trials over several years has meant that it is not possible to sow all RL varieties every year as is done with some species.

Table 1.3 gives typical numbers of herbage varieties at each stage of testing in a five year period.

1.4.2 Criteria for decisions

DM yield is the major character used in judging the value of new varieties for NL and RL purposes, as is the case for most crops. Herbage differs from single harvest crops however in the many ways that yield can be measured - individual cuts, totals over several cuts, each recorded for two harvest years and each with separate cutting managements. All of these aspects of yield are balanced and taken into account when reaching a decision on the future of a variety. Apart from DM yield, other characters of

Table 1.3: Numbers of varieties sown in trials 1974-78

YEAR OF SOWING	PRG	IRG	TIM	CFT	RCL
	no. at NL1 : no. at NL2 : no. of controls and re-tests				
1974	17:22:12	8:10:3	4:10:5	2:2:2	13:5:3
1975	19:16:24	10: 4:8	0: 4:6	5:2:3	8:5:5
1976	24:17:10	12: 8:4	1: 1:6	4:4:2	5:8:5
1977	19:19:13	14:12:5	4: 1:4	5:3:3	3:6:7
1978	29:19:13	11:13:6	2: 4:4	5:5:3	0:3:5
Total	108	55	11	21	29
Added to NL	36	7	9	5	14
Added to RL	18	7	2	4	9

importance are, digestibility, persistency, winter-hardiness and disease resistance.

1.4.3 Inter-variety comparisons

In both NL and RL work, comparisons are restricted to varieties within the same maturity and ploidy group.

For the NL, the only comparison necessary is that between the new and the control variety. The control is used as a base line against which the value of the new variety is assessed. How the new variety performs relative to other varieties on the NL, is not of direct interest in reaching NL decisions.

For the RL, the form in which it is presented requires that an estimate be given of the relative performance of all varieties on the list. Furthermore, varieties on the RL are reviewed continually and may be removed in the light of more experience or the introduction of newer varieties. Thus for RL purposes, comparisons are required amongst all existing and candidate varieties.

1.4.4 Summarising trials data

The primary aim in analysing official trials data is to provide an accurate and unbiased estimate of the average response of the varieties in the conditions in which they will be grown in practice.

A secondary objective is to identify, where possible, environments in which an individual variety's performance may depart from the average, e.g. areas that are subject to severe frost, or to indicate special features of a variety's general behaviour, e.g. above-or below-average consistency of performance.

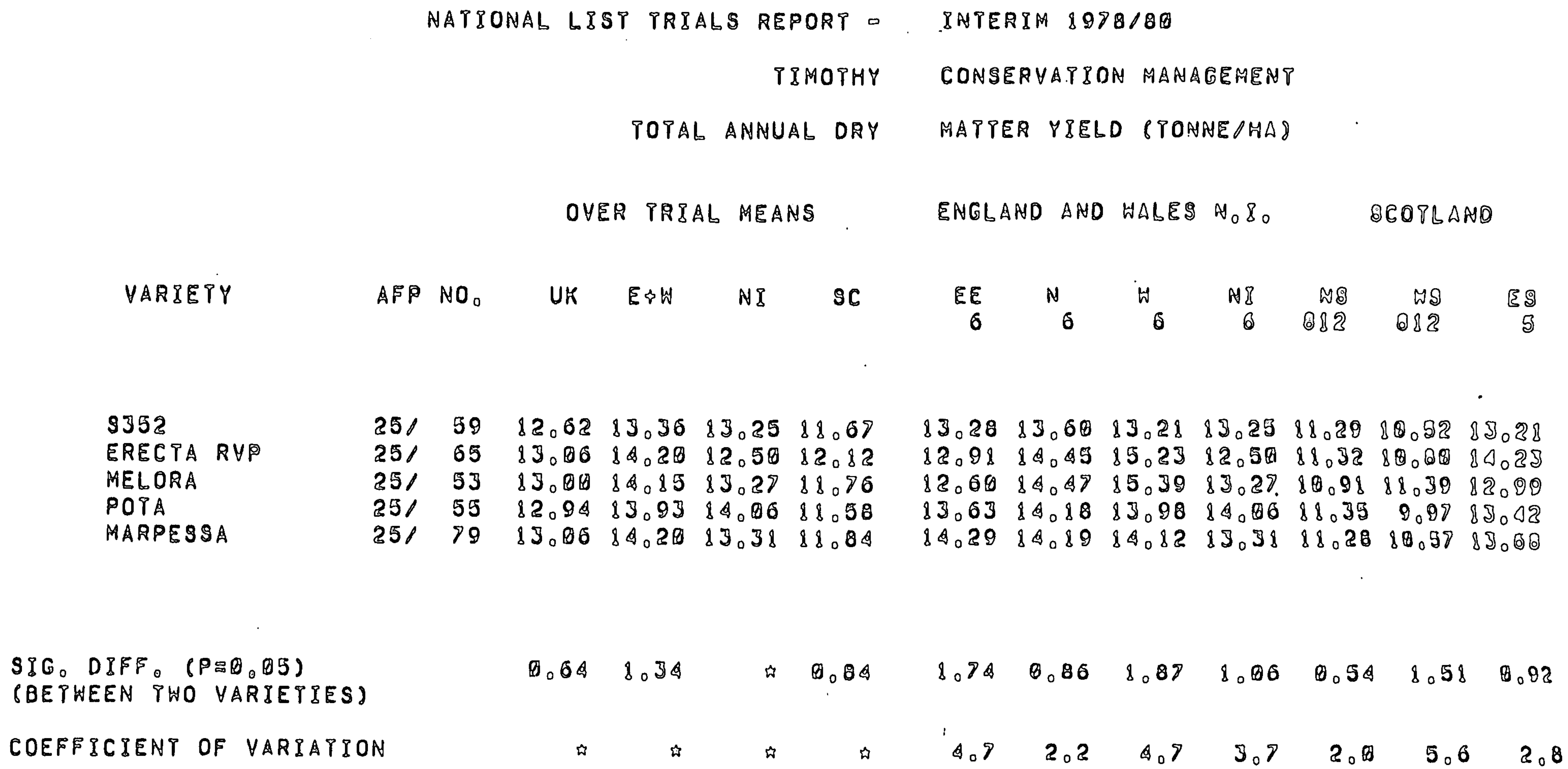
The estimation of average variety performance involves a two-stage scheme of analysis in which a summary of the results from one stage provides the basic data for the next stage. Thus plot observations are averaged to give variety means for each trial. The trial means are then summarised to form annual means. However this process is not carried through to using annual means to estimate over-years means. At present, over-years means are estimated by averaging results from individual trials.

For NL purposes the estimation of average variety performance is straightforward. Since the only comparison of interest is that of the candidate with the control variety and as both are sown in each trial, the difference between the two varieties, averaged over trials, provides an estimate of the value of the new variety. Figure 1.8 is an example of a one-year NL report.

In RL work the estimation of relative variety performance is more complex. Few of the established varieties will have been sown in the same trials as the new varieties. Many of the established varieties will not have been sown with each other. The only common variety link between trials is likely to be the control variety. Even this may change over years since an analysis bringing together the most recent information on all RL varieties can span more than ten years of trials.

Figure 1.9 illustrates the structure of a typical data matrix of variety x year means from which estimates of average variety performance are produced. Generally, all varieties in trial are sown at every centre. Occasionally however, trials may not be sown at a centre or may fail to establish.

Figure 1.8: Example of one-year NL herbage variety trials report



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                         NATIONAL LIST TRIALS REPORT -   INTERIM 1978/80

                                           TIMOTHY   CONSERVATION MANAGEMENT

                                 TOTAL ANNUAL DRY   MATTER YIELD (TONNE/HA)

                           OVER TRIAL MEANS          ENGLAND AND WALES N.I.         SCOTLAND

   VARIETY          AFP NO.     UK    E+W     NI     SC       EE      N      W     NI     NS     WS     ES
                                                              6      6      6      6    012    012      5


  S352              25/  59  12.62  13.36  13.25  11.67    13.28  13.60  13.21  13.25  11.29  10.52  13.21
  ERECTA RVP        25/  65  13.06  14.20  12.50  12.12    12.91  14.45  15.23  12.50  11.32  10.00  14.23
  MELORA            25/  53  13.00  14.15  13.27  11.76    12.60  14.47  15.39  13.27  10.91  11.39  12.99
  POTA              25/  55  12.94  13.93  14.06  11.58    13.63  14.18  13.98  14.06  11.35   9.97  13.42
  MARPESSA          25/  79  13.06  14.20  13.31  11.84    14.29  14.19  14.12  13.31  11.28  10.57  13.68


SIG. DIFF. (P=0.05)           0.64   1.34      ☆   0.84     1.74   0.86   1.87   1.06   0.54   1.51   0.92
(BETWEEN TWO VARIETIES)

COEFFICIENT OF VARIATION         ☆      ☆      ☆      ☆      4.7    2.2    4.7    3.7    2.0    5.6    2.8
```

Figure 1.9; Example of data matrix for estimating RL variety performance - each figure in table is based on mean of several trials.

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 ++++ NATIONAL/RECOMMENDED LIST VARIETY TRIALS ++++

ITALIAN RYEGRASS RL CONSERVATION TRIALS 1968-79

TOTAL ANNUAL YIELD(TONNE/HA)IN FIRST HARVEST YEAR


                                        SOWN / HARVESTED

                        68    69    70    71    72    73    74    75    76    77    78    79

  VARIETY       MEAN    69    70    71    72    73    74    75    76    77    78    79    80

RVP             17.2  18.0  15.0  16.6  17.6  19.0  20.4  15.5  12.5  18.6  17.5  17.5  18.2
LEMA            16.0  16.8  13.9     ☆     ☆     ☆     ☆     ☆     ☆     ☆  16.5     ☆     ☆
SABALAN         16.3     ☆  14.3  14.4  17.0  19.4     ☆     ☆     ☆     ☆     ☆     ☆     ☆
SABEL           16.1     ☆     ☆     ☆  16.4  19.5  18.9     ☆     ☆     ☆     ☆     ☆     ☆
SABRINA         15.5     ☆     ☆     ☆  16.1  18.1     ☆     ☆     ☆     ☆     ☆     ☆     ☆
COMBITA         15.7     ☆     ☆     ☆  16.3     ☆     ☆     ☆     ☆     ☆     ☆  15.3     ☆
OPTIMA          15.6     ☆     ☆     ☆  15.1     ☆     ☆     ☆     ☆     ☆     ☆  15.5  16.9
DELTEX          17.0     ☆     ☆     ☆     ☆  20.1     ☆  15.1  12.3     ☆     ☆     ☆     ☆
AUGUSTA         15.5     ☆     ☆     ☆     ☆     ☆  18.9  15.0     ☆     ☆     ☆     ☆  14.9
TRIDENT         17.5     ☆     ☆     ☆     ☆     ☆  21.6  15.2     ☆     ☆     ☆     ☆     ☆
WILO            16.8     ☆     ☆     ☆     ☆     ☆     ☆     ☆  12.6  17.7     ☆     ☆     ☆
LIPO            17.2     ☆     ☆     ☆     ☆     ☆     ☆     ☆  12.6  18.4     ☆     ☆     ☆
AKA             17.3     ☆     ☆     ☆     ☆     ☆     ☆     ☆  12.6  18.7     ☆     ☆     ☆
WHISPER         16.4     ☆     ☆     ☆     ☆     ☆     ☆     ☆     ☆  17.8  16.7     ☆     ☆
TITANIA         16.1     ☆     ☆     ☆     ☆     ☆     ☆     ☆     ☆     ☆  16.8  15.8     ☆
TOLMAN          16.2     ☆     ☆     ☆     ☆     ☆     ☆     ☆     ☆     ☆  16.5  16.1     ☆
MULTIMO         17.0     ☆     ☆     ☆     ☆     ☆     ☆     ☆     ☆     ☆  17.4  17.0     ☆
SIRIOL          15.1     ☆     ☆     ☆     ☆     ☆     ☆     ☆     ☆     ☆  15.8  14.7     ☆
```

1.4.5 Checking departures from average

The main check on systematic departures from the average is done by producing variety means separately for each part of the country. Results are also compiled year by year. Procedures are available for printing residuals from variety x trials tables.

1.5 ORGANISATION OF THE THESIS

The aim of a variety testing programme is to identify with minimum selection error those varieties which will give improved value in commercial use. Selection error can be minimised either by controlling the sampling variation or by reducing the measurement error. Much of this thesis deals with these two aspects of selection error.

Measurement error is considered in Chapter 2 where methods for the control of within-trial variation are reviewed and proposals are made. In Chapter 3 attention is directed to describing the main sources of sampling variation in recent UK herbage variety trials. Techniques used in the estimation of components of variation are outlined. Chapter 4 is concerned with ways in which sampling variation can be reduced by stratification. The additional information provided by such techniques in herbage variety testing is examined. In Chapter 5 methods for the estimation of future variety performance are critically reviewed. Finally in Chapter 6 the design of a variety testing programme is considered with the objective of minimising selection error.

1.6 LITERATURE REVIEW

1.6.1 Design of individual trials

The work of R.A. Fisher is the basis for much of present experimental design practices in variety testing. Until forty-five years ago virtually all variety trials were set out in systematic order. Fisher (1925) showed how the effects of inter-plot variability in field experiments can be reduced by blocking and analysis of variance, while randomisation of treatments to plots could give unbiased estimates of experimental error. Randomised block designs were quickly adopted for variety testing and have been in regular use in the UK since 1935.

F. Yates (1936) brought together Fisher's ideas on blocking and factorial systems and applied them to the needs of plant breeders for block designs using many varieties. Square lattice designs, as they became known, have the essential property for variety testing work of being resolvable. This permits cultivation and measurement to be done on a complete replication at a time. However a serious restriction for official variety trials is the limited numbers of varieties for which designs are available ($v = s_{*}s$ where v and s are the numbers of varieties and blocks per replicate).

Harshbarger (1949) extended the range of lattices to rectangular lattices ($v = s(s-1)$). Even this extension does not meet fully the requirements of variety testing (Silvey, 1967).

Bose and Nair (1962) considered the construction of resolvable two-replicate designs but their method does not generalise to larger numbers of replicates.

Patterson and Williams (1976), in work directed specifically to the needs of official variety testing in the UK, extended the basic principles of standard lattice designs to produce a catalogue of very efficient resolvable lattice designs for $r = 2, 3, 4$; $v \leq 100$; $4 \leq k \leq 16$, where k is the number of plots per small block. They defined a class of designs, called alpha- designs, which included as special cases some standard lattice designs. A cyclic method of construction was used to generate designs and those with the highest efficiency factors (Yates, 1936) were chosen for inclusion in the catalogue. The basic method produced designs with equal block sizes but Patterson and Williams showed how these could be adapted when v is not a multiple of k to give designs with a mixture of k and $k - 1$ plots per block.

The construction of incomplete block designs by cyclic methods has been considered in several studies (David, 1967; John, Wolock and David, 1972; Jarrett and Hall, 1978). While all of the methods can produce resolvable designs, no one method covers the complete range of design parameters considered by Patterson and Williams.

1.6.2 Analysis of individual trials - univariate

Early experimenters recognised the need to correct for positional effects in plot trials. Several methods were suggested. One of these was the contingency method (Pearl and Surface, 1916) which involved correcting for the yield of a plot by a function of the yield of the row and column in which it occurred.

Fisher's work unified the design and analysis stages. The orthogonal structure of the complete block and latin square arrangements meant that adjustment of observations was not required and experimental error was estimated simply.

The introduction of lattice designs inevitably made the analysis stage more complex. Yates (1940) emphasised the importance of combining, as a routine, the separate estimates of the treatment effects from inter- and intra-block comparisons for maximum efficiency when block effects are negligible. In his paper, Yates showed how this might be done.

It was a generalisation of the Yates' method that Williams (1977) described for use in the analysis of Patterson and Williams alpha-designs. These designs necessarily sacrificed some computational simplicity at the analysis stage. However the designs were chosen so as to give narrow ranges of variances for pairs of varieties with equal concurrences. This facilitates the presentation of results since only two or three standard errors are necessary.

An extension of earlier methods of correcting for position was suggested by Papadakis (1937). His proposal for adjusting yields by covariate formed from the residuals of neighbouring plots has been investigated in several studies (Bartlett, 1938; Atkinson, 1969; Bartlett, 1978). Bartlett concluded that where the number of plots is large, then the method should be approximately valid and sometimes useful. Atkinson showed that Papadakis estimates closely approximate maximum likelihood estimates. Some empirical investigations (Pearce and Moore, 1976; Kempton and Howes, 1981) have shown that the method can be very effective in reducing between-plot variation. Reservations remain: the theoretical basis of the Papadakis method is not fully understood; the extent to which the reduction in variance truly reflects increased accuracy is questioned; the consequences of competition and inter-treatment effects are unclear.

1.6.3 Individual trials - multivariate analysis

In analysing data from perennial crop experiments, a method often adopted is to treat different harvests as an additional factor in an analysis of variance (for example, Pearce, 1953, page 14). Some of the possible consequences of this approach in the analysis of long-term experiments, have been considered by several statisticians (Cochran, 1940; Patterson, 1953). Cochran (1940) gave an example of sugar cane data where yields from successive harvests were positively correlated. Use of a pooled error from individual seasons seriously underestimated the true error of the difference between treatment means. Cochran (1939) cited experiments with apple trees and with pyrethrum, where negative correlations between the same plots in different seasons were noted.

A multivariate approach which took account of the correlations between harvest years was used by Steel (1955) in an analysis of two seasons' yields from an alfalfa trial of 25 varieties. He derived two canonical variates representing linear functions of the annual yields which gave maximum discrimination between varieties while being uncorrelated with each other. Finney (1956) questioned the use of canonical analyses as applied to Steel's variety trial data. He considered that the statistical analysis should have been concerned with determining the error variance rather than with tests for significance, since by their nature varieties must differ to some degree in yield potential, and tests of significance would tend to measure the adequacy of the experiment. Finney also emphasised that the variates to be analysed should be determined by the purposes of the experiment rather than be derived from internal statistical analysis. He suggested that in Steel's data, an analysis of the sum, and then of the difference, of the two harvest years' yield would have been more useful to an experimenter than canonical analysis.

The application of multivariate analysis of variance to repeated-measurement experiments has been illustrated in several papers (Cole and Grizzle, 1966; Danford, Hughes and McNee, 1960). Wishart (1938) used a univariate analysis of coefficients derived by fitting polynomial equations in time to growth measurements. This approach was advocated subsequently by Rowell and Walters (1976). Evans and Roberts (1979) pointed out that the polynomial coefficients will be correlated and suggested a multivariate analysis of variance applied to coefficients derived by fitting polynomial equations to treatment contrasts rather than to the original observations. In all of these investigations the primary objective was to test for treatment and treatment x time effects rather than to estimate the actual effects.

1.6.4 Series of trials

Yates and Cochran (1937) examined the application of analysis of variance to the results of a series of trials. They showed, through examples, how such an analysis differed from that applied to a single replicated experiment. In data from a series of wheat variety trials, they identified heterogeneous variety x trial terms where one variety responded differentially to changes in fertility. In data from sugar beet trials they demonstrated how heterogeneity of within-trial errors could lead to false conclusions. Yates and Cochran also set out clearly the conditions which must be attached to inferences made from the statistical analyses of series of trials.

Much of the literature since Yates and Cochran's (1937) paper has been concerned with the development of increasingly more complex models of trials systems and the application of these models, particularly in the area of plant breeding and variety testing. This work has been reviewed by Freeman (1973). Four themes can be identified in this work, all of which are closely related but in the main have developed separately:

> Individual variety x environment interaction terms were studied, primarily through the regression methods suggested by Yates and Cochran but extended by Finlay and Wilkinson (1963), Eberhart and Russell (1966), Shukla (1972a), Hardwick and Wood (1972), Digby (1979);
>
> General variety x environment components of variance from past trials were estimated and used to determine the optimum allocation of trial resources (Sprague and Federer, 1951; Rasmusson and Lambert, 1961; Hanson, 1964; Kaltsikes, 1970; Patterson et al, 1977);
>
> Breeding selection systems were simulated to determine optimal proportion of varieties for selection after each stage of testing (Finney, 1958; Curnow, 1961; Young, 1972);

A multivariate approach was used in which data for varieties or environments were treated as separate variates and principal components calculated and checked for association with other variables, or alternatively, principal coordinates were derived and varieties or environments classified (Shukla, 1972b; Freeman and Dowker, 1973; Freeman, 1975; Freeman and Crisp, 1979).

Some of the developments described above, were brought together by Patterson and Silvey (1980) in a review of statistical procedures in RL and NL cereal variety testing in the UK. They defined several variety x environment models: a general model allows for complete heterogeneity of variety variances; a simple model involves the use of a single variety x environments variance term; an intermediate model includes variance terms for the linear responses of individual varieties to changes in environment, i.e. similar to the Yates-Cochran joint regression approach. Each of these models can be extended by sub-dividing the environment component into centres, years, and centres x years terms, and dividing the variety x environment component similarly.

In their paper, Patterson and Silvey explain that it is the simple model which is applied to the routine estimation of cereal variety performance, using the technique of fitting constants (Yates, 1933). They outline the circumstances in which the simple model can be expected to operate satisfactorily. They also indicate how the extended simple model is used to guide on the allocation of trial resources.

All of the references detailed here are concerned with the analysis of data from a series of single harvest trials. I have not located references to work on statistical aspects of series of multiple-harvest trials.

CHAPTER 2

CONTROL OF EXPERIMENTAL ERROR

2.1 INTRODUCTION

2.1.1 Preface

Several plots of each variety are sown in every official herbage variety trial. The variation in variety response between plots is usually called experimental error. In small plot field-work, experimental error gives little useful information on the way a variety's performance will change over environments in commercial practice. The aim in trials is therefore to control and minimise experimental error.

In this chapter the main sources of experimental error in herbage variety trials are identified. One source - soil heterogeneity - is examined closely. Its control through the use of lattice designs is considered. Methods for the combined analysis of individual cut and total yield data from lattice-designed experiments are investigated.

2.1.2 Sources of experimental error

Experimental error in plot field trials may result from,

measurement error,
variation between plants,
differences in fertility between plots.

Measurement error can occur in several ways: there may be inaccuracies in cutting and weighing yields; the sample taken for drying may not be representative of the total harvested yield; errors may occur in recording or data processing. Of these, DM sampling is potentially the most important source of measurement error, since the weight of sample taken for drying can constitute as little as 1/100th of the total yield. Although this aspect merits investigation it is not considered further here. The other sources of measurement error are controlled by good experimental techniques.

Variation between plants is likely to be larger in cross-pollinated species such as grasses than in self-pollinated crops such as cereals. Nevertheless, relative to other factors it is unlikely to be a substantial source of experimental error.

Soil heterogeneity is a major influence on experimental error. To compare varieties effectively it is desirable that they are sown under conditions as similar as possible. This is difficult once there are more than a few varieties since it is a universal experience that while areas of ground close together are similar distant areas are different. The effect of soil heterogeneity may be controlled through experimental design as well as through choice of size, shape and orientation of plots. In herbage variety trials the choice of plot size and shape is based on trials experience over many years, and represents a practical compromise between the need for least error and minimum cost. The use of design for controlling the effects of experimental variability is considered in the next section.

2.2 CONTROL OF EXPERIMENTAL VARIABILITY THROUGH DESIGN

2.2.1 Basic principles

The basic principles of experimental design are randomisation, replication and local control (the arrangement of plots in blocks or in a systematic order). Replication and local control have long been in use for field experiments. Randomisation was introduced by R.A. Fisher to provide valid estimates of the variability underlying the mean estimates.

2.2.2 Randomisation

Randomisation of varieties to plots in the field is accepted as good experimental practice in official NL and RL trials. It permits valid estimates of experimental error and, while these estimates are not required for tests of significance in variety performance trials, they do have a useful role in monitoring the trial's system. More importantly, randomisation provides the assurance that treatment means will be estimated without bias. This assurance is far more valuable in variety testing, which relies for its viability on the confidence of many, rather than any reduction in average variance that might be achieved by a systematic arrangement.

2.2.3 Replication

An increase in the number of plots of each variety is the most direct route to reducing experimental error. For complete block arrangements, increasing replication from two to three plots will give an average 33% reduction in experimental variance. It will also permit a more satisfactory check on possible aberrant plot values and provide more secure estimates of missing values.

As an alternative to increasing replication of all varieties, greater replication of the control varieties may be considered, since NL comparisons are required only between test and control varieties. An extra plot of the control in each replicate will reduce the variance of comparisons with the control. However, because separate controls are required for different maturity and ploidy groups, such a change might require an increase in the number of plots by up to 15%. Furthermore, official trials are used for RL purposes where all variety comparisons are equally important.

2.2.4 Local control

Several methods for local control of experimental variability are available. Treatments may be applied to units that are as similar as possible. This is done in field plot experiments by assigning treatments to plots that are close together (in blocks of plots), and by subsequent management of the plots in a uniform manner. Alternatively, or as a supplement to blocking, secondary variables may be used to adjust at the analysis stage for differences between experimental units.

The procedure used for local control in herbage variety trials is that of complete blocks. A complete block contains as many plots as there are varieties and all varieties are sown in each block. Table 2.1 shows that the average variation removed by complete blocks in Scottish herbage variety trials is small, though not negligible.

Since the number of plots per block is large in many of the herbage variety trials, it seems reasonable to assume that the

Table 2.1: Within-trial mean squares (tonne/hectare)^2 in analysis of variance of DM yield in Scottish herbage trials 1974-78

SPECIES	SOURCE	HARVEST YEAR	CONSERVATION						FREQUENT					
			cut group 1 mean squares	cut group 2 mean squares	cut group 3 mean squares	cut group 4 mean squares	Total	No. trials/ varieties	cut group 1 mean squares	cut group 2 mean squares	cut group 3 mean squares	cut group 4 mean squares	Total	No. trials/ varieties
PRG	Blocks	1	1.19	.19	.09	.05	1.41	69/10	.09	.31	.43	.09	1.36	18/42
		2	.43	.13	.07	.03	.71		.13	.30	.30	.03	.99	
	Residual	1	.34	.06	.03	.01	.44		.03	.05	.06	.01	.23	
		2	.25	.04	.04	.02	.38		.02	.05	.06	.01	.21	
IRG	Blocks	1	1.51	.12	.09	.11	3.09	36/5	.23	.12	.15	.02	.60	15/25
		2	.45	.10	.07	.14	1.37		.43	.29	.17	.04	.77	
	Residual	1	.37	.03	.03	.03	.52		.04	.03	.06	.01	.21	
		2	.22	.03	.02	.03	.34		.04	.05	.06	.01	.22	
TIM	Blocks	1	.33	.09	.09	.01	.77	30/4	.12	.10	.04	.01	.30	14/11
		2	.36	.08	.14	.02	.65		.16	.08	.15	.02	.57	
	Residual	1	.20	.02	.04	.01	.27		.04	.03	.04	.01	.11	
		2	.14	.04	.04	.01	.22		.02	.03	.04	.00	.11	
CFT	Blocks	1	.16	.03	.03	.04	.34	22/4	.07	.08	.06	.02	.25	10/12
		2	.26	.01	.01	.05	.38		.05	.07	.14	.00	.24	
	Residual	1	.10	.01	.03	.02	.21		.02	.05	.03	.00	.12	
		2	.08	.01	.02	.02	.15		.01	.04	.02	.00	.09	
RCL	Blocks	1	1.40	.39			2.00	28/7						
		2	1.08	.62			2.02							
	Residual	1	.55	.15			.72							
		2	.53	.09			.67							

residual variation can be further reduced. Figure 2.1 shows the relationship between block size and residual variation in Scottish perennial and Italian ryegrass frequent management trials. Even though the relation ship is confounded with other between-trial factors, and is therefore inaccurately determined, a trend is apparent of variances increasing with block size, at least in perennial ryegrass.

A method, considered by several authors for control of experimental variability in large trials, was suggested by J.S. Papadakis (1937) for adjusting yields by covariance on residuals from neighbouring plots. Unfortunately, as pointed out by Yates (1970, page 148), the method can exaggerate competition and other inter-treatment effects. Thus, a treatment which diminishes the yield of neighbouring plots, perhaps through its more vigorous growth, or as a disease-initiator, will have its relative yield enhanced by covariance adjustment on neighbouring residuals. On the other hand, a treatment whose yield is decreased by disease which does not affect other treatments will have its yield underestimated. These are serious defects in variety testing where bias in estimating treatment effects cannot be compensated for, by increasing accuracy.

The use of lattice designs is an obvious way of reducing block size, and hence diminishing error. Various sources of lattice designs are available but the catalogue of alpha-designs by Patterson and Williams (1976) is the most comprehensive for variety testing purposes. Alpha-designs have been in routine use with UK cereal variety trials for several years and have shown, with 20 or more varieties, a median efficiency of 1.40 relative to complete

Figure 2.1: Block size and within experiment plot variance
- data are total season DM yield from Scottish trials 1974-78

Expt. error variance (tonne/ha)^2

```
      -+---------+---------+---------+---------
0.500 I                                       I
0.471 I                             *         I
0.441 I                                       I
0.412 I                       *        *      I
0.382 I                                       I
0.353 I                                  *    I
0.324 I                                       I
0.294 I             *               *         I
0.265 I                                       I
0.235 I                                       I
0.206 I                                2 *    I
0.176 I                                  *    I
0.147 I                       2               I
0.118 I                         2             I
0.088 I             2               *         I
0.059 I                         *             I
0.029 I                                       I
0.000 I                                       I
      -+---------+---------+---------+---------
       0         16        32        48
```

PRG

No. of plots/block

Expt. error variance (tonne/ha)^2

```
      -+---------+---------+---------+---------
0.500 I                                       I
0.471 I                                       I
0.441 I                                       I
0.412 I                                       I
0.382 I         *                             I
0.353 I                    *                  I
0.324 I         *                             I
0.294 I                *                      I
0.265 I         *                             I
0.235 I                   **                  I
0.206 I                2                      I
0.176 I                                       I
0.147 I         *                             I
0.118 I                   2*                  I
0.088 I         2                             I
0.059 I                                       I
0.029 I                                       I
0.000 I                                       I
      -+---------+---------+---------+---------
       0         16        32        48
```

IRG

No. of plots/block

block designs (Patterson and Silvey, 1980). Similar types of design, but from the Jarrett and Hall (1978) series, are in use in Australia.

A further factor favouring the use of lattice designs in herbage variety trials is the recent introduction of a new plot harvester which is less manoeuverable than earlier mowers. To minimise turning space and to permit maximum efficiency at harvest, it is desirable to sow a two-replicate trial in four banks of plots. A lattice design would facilitate the division of each replicate into two banks which, when placed behind each other, would give the run of four plots required for harvesting. This arrrangement is possible only with an even number of varieties, since oddly shaped banks are unlikely to be acceptable in the field. Suitable two-replicate alpha-designs are currently available for even numbers of varieties from 4 to 100. For trials with numbers of varieties that require unequal block sizes, a restriction must be placed on the randomisation of small blocks within replicates. For example, in a trial with 22 varieties where each replicate is divided into two banks of 11 plots, and small blocks with 5 and 6 plots per block are used, then one of each size of block must be assigned to a bank. This restriction applies to trials with numbers of varieties 22, 26, 34, 38, 46, 58, 62, 68, 74, 76, 82, 86, 92 and 94.

Estimates of the potential reduction in experimental variance to be obtained from some of the methods considered above are summarised in Table 2.2. Alpha designs are nearly as effective as an additional replicate in reducing experimental variability.

Table 2.2: Efficiency of methods for control of experimental variability
- an examination of total season DM yield from 14 Scottish PRG frequent management trials 1974-78

CONTROL METHOD	% REDUCTION IN VARIANCE (i)	% ADDITIONAL PLOTS REQUIRED
Complete block (2 reps)	6(7)	0
Complete block (3 reps)	37(38)	50
Complete block (ii) (2 reps + 1 extra control)	29(31)	10-15
Alpha-design	- (32)	0

Notes: (i) Average % reduction in the within-trial variance of a variety difference, relative to a two-replicate completely randomised arrangement. Figures in parenthesis are from a single alpha-designed trial sown with 37 varieties in 2 replicates and small blocks of 4 and 5 plots;

(ii) % reduction in variance of comparisons with control only; variance of other contrasts are not affected;

Although these results are from only a single trial, they are broadly in line with experience in other crops.

In the past, some reluctance has been shown to the use of lattice designs in herbage variety trials, even amongst statisticians. The reluctance stems from uncertainty concerning the joint analysis of individual-cut and total-over-cuts data. This uncertainty is principally focussed on the difference which occurs between the sum of the adjusted mean yields from the individual cuts and the adjusted means for total yield. Table 2.3 illustrates the point, though in this example the difference is small - not more than 0.7% of mean yield.

The next section attempts to resolve the uncertainty concerning the lattice analysis of multiple-cut data. The simple example of two cuts is taken and used to explore the relative efficiency of several joint-analysis procedures. Possibly the most serious consequence of inefficiencies in analysis procedures is the lack of consistency between estimates of mean yield for individual cuts and totals over two or more cuts, as occurs in the example in Table 2.3

TABLE 2.3: COMPARISION OF LATTICE-ADJUSTED MEANS FOR INDIVIDUAL CUTS AND TOTAL OVER CUTS YIELDS. -DATA FROM PRG FREQUENT MANAGEMENT TRIAL.

	HARVEST YEAR 1		HARVEST YEAR 2		HARVEST YEAR 3	
VARIETY	(A)	(B)	(A)	(B)	(A)	(B)
1	-0.055	-0.209	-0.035	0.029	-0.015	-0.054
2	0.039	0.203	-0.003	0.043	0.024	0.399
3	0.037	0.235	0.010	0.068	-0.006	0.092
4	-0.018	-0.223	0.031	-0.143	-0.007	-0.451
5	-0.021	-0.119	0.001	-0.025	-0.016	-0.261
6	0.011	0.039	-0.014	0.036	-0.018	0.213
7	0.021	0.266	-0.019	0.080	0.066	0.557
8	-0.008	-0.181	0.035	-0.094	-0.035	-0.524
9	-0.011	-0.076	0.004	0.024	-0.044	-0.333
10	0.045	0.129	0.022	-0.018	-0.019	0.006
11	-0.007	0.102	-0.030	0.073	0.024	0.371
12	-0.024	-0.150	0.006	-0.083	0.036	-0.059
13	-0.027	-0.045	-0.024	0.036	0.027	0.132
14	0.027	0.192	0.006	0.019	0.023	0.165
15	-0.052	-0.314	-0.005	-0.090	-0.006	-0.244
16	0.055	0.172	0.026	0.031	-0.047	-0.066
17	-0.055	-0.209	-0.035	0.029	-0.015	-0.054
18	0.039	0.203	-0.003	0.043	0.024	0.399
19	0.037	0.235	0.010	0.068	-0.006	0.092
20	-0.018	-0.223	0.031	-0.143	-0.007	-0.451
21	0.011	0.039	-0.014	0.036	-0.018	0.213
22	-0.021	-0.119	0.001	-0.025	-0.016	-0.261
23	0.021	0.266	-0.019	0.080	0.066	0.557
24	-0.008	-0.181	0.035	-0.094	-0.035	-0.524
25	-0.011	-0.076	0.004	0.024	-0.044	-0.333
26	0.045	0.129	0.022	-0.018	-0.019	0.006
27	-0.007	0.102	-0.030	0.073	0.024	0.371
28	-0.024	-0.150	0.006	-0.083	0.036	-0.059
29	-0.027	-0.045	-0.024	0.036	0.027	0.132
30	0.055	0.172	0.026	0.031	-0.047	-0.066
31	0.027	0.192	0.006	0.019	0.023	0.165
32	-0.052	-0.314	-0.005	-0.090	-0.006	-0.244
33	-0.011	-0.076	0.004	0.024	-0.044	-0.333
34	0.045	0.129	0.022	-0.018	-0.019	0.006
35	-0.007	0.102	-0.030	0.073	0.024	0.371
36	-0.024	-0.150	0.006	-0.083	0.036	-0.059
37	-0.027	-0.045	-0.024	0.036	0.027	0.132
MEAN DIFF.	0.000	0.000	0.000	0.000	0.000	0.000
MEAN YIELDS	8.15		7.41		10.39	

NOTES : (A) ADJUSTED MEAN FOR TOTAL YIELD MINUS SUM OF ADJUSTED MEAN YIELDS FROM INDIVIDUAL CUTS.

(B) ADJUSTED MEAN FOR TOTAL YIELD MINUS SUM OF UNADJUSTED MEAN YIELDS FROM INDIVIDUAL CUTS.

2.3 THE ANALYSIS OF MULTIPLE HARVEST DATA

In this section, a general model is defined to describe the joint analysis of data from two cuts. Three methods of estimating variety contrasts from the model are outlined, and formulae expressing the relative efficiency of each of the methods are derived. The relative efficiencies are examined algebraically for three specific cases of the model and by exploration of the general model for several parameter value settings.

The estimation methods considered are as follows.

1. The univariate analysis of data from individual cuts with full recovery of inter-block information but ignoring information on the model parameters that is available from other cuts as a consequence of correlations between cuts. This method also provides estimates for totals over cuts derived from the sum of the individual cut estimates.
2. The univariate analysis of plot totals with full recovery of inter-block information but ignoring information from individual cuts.
3. A fully efficient bivariate analysis which gives estimates for individual cuts and for totals over cuts with full recovery of inter-block information, and which also takes into account between-cut correlations.

2.3.1 Model definition

Suppose data are available for two cuts from an experiment laid down as a lattice design. We wish to estimate the same variety contrast in each cut, and in the totals over cuts. For each cut, there will be information on the contrast from two strata: between blocks and between plots within blocks.

Let Y_{Wi} be an efficient within-block estimate of the variety contrast in cut i, and let Y_{Bi} be an estimate of the same contrast, also in cut i, but based on information from between blocks, i.e.

	Cut 1	Cut 2
Stratum B	Y_{B1}	Y_{B2}
Stratum W	Y_{W1}	Y_{W2}

The expectation of y, the column vector formed from Y_{ji} $(j = B, W; \; i = 1, 2)$, is given by

$$E(y) = A\theta$$

in which

$$y = \begin{bmatrix} Y_{B1} \\ Y_{W1} \\ Y_{B2} \\ Y_{W2} \end{bmatrix} ; \qquad \theta = \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix} ,$$

θ_1 and θ_2 being the variety contrasts that are to be estimated from cuts 1 and 2; and where

$$A = \begin{bmatrix} 1 & 0 \\ 1 & 0 \\ 0 & 1 \\ 0 & 1 \end{bmatrix}$$

is a matrix in which an element is 1 if there is information on the column contrast in the row estimate, otherwise zero.

The variance of y may be specified as follows:

$$V = V(y) = \begin{bmatrix} \lambda_1 v_1 & & c_B & \\ & v_1 & & c_W \\ c_B & & \lambda_2 v_2 & \\ & c_W & & v_2 \end{bmatrix} \qquad (2.3.1.1)$$

where λ_i is the ratio $\frac{\text{var } Y_{Bi}}{\text{var } Y_{Wi}}$, $i = 1, 2$; and v_i is var Y_{Wi}.

c_B and c_W must satisfy the equations

$$\rho_B = \frac{c_B}{\surd(\lambda_1 \lambda_2 v_1 v_2)},$$

$$\rho_W = \frac{c_W}{\surd(v_1 v_2)}$$

where ρ_B and ρ_W are the between-and within-block correlations between cuts.

In the analysis of lattice experiments, λ_i is the ratio of the weights for between-and within-block estimates in the recovery of inter-block information.

2.3.2 Methods for estimating $\theta_1, \theta_2, \theta_1+\theta_2$

Method 1: Univariate analysis of each cut.

This method estimates θ_1 efficiently using cut 1 data but ignoring cut 2 results and estimates θ_2 efficiently ignoring cut 1 results. The estimates are $\tilde{\theta}_1, \tilde{\theta}_2, \tilde{\theta}_1+\tilde{\theta}_2$ where

$$\tilde{\theta}_i = \frac{Y_{Bi} + \lambda_i Y_{Wi}}{1 + \lambda_i},$$

and where $\tilde{\theta}_1 + \tilde{\theta}_2$ is the simple sum of the individual cut estimates. The variance matrix is

$$V(\tilde{\theta}) = \begin{bmatrix} \text{var } \tilde{\theta}_1 & \text{cov}(\tilde{\theta}_1, \tilde{\theta}_2) \\ \text{cov } (\tilde{\theta}_1, \tilde{\theta}_2) & \text{var } \tilde{\theta}_2 \end{bmatrix} \qquad (2.3.2.1)$$

where $$\text{var } \tilde{\theta}_i = \frac{v_i \lambda_i}{1+\lambda_i}$$

and $$\text{cov}(\tilde{\theta}_1, \tilde{\theta}_2) = \frac{\sqrt{\lambda_1 \lambda_2 v_1 v_2}(\rho_B + \rho_W \sqrt{\lambda_1 \lambda_2})}{(1+\lambda_1)(1+\lambda_2)}.$$

Method 2: Univariate analysis of totals over cuts.

In this analysis the estimate θ_* (of $\theta_1+\theta_2$) is the weighted mean of $y_{B1} + y_{B2}$ and $y_{W1} + y_{W2}$. These elements are independent and have variances given by

$$\mathrm{var}(y_{B1} + y_{B2}) = \lambda_1 v_1 + \lambda_2 v_2 + 2c_B = V_B$$

$$\mathrm{var}(y_{W1} + y_{W2}) = v_1 + v_2 + 2c_W = V_W \ .$$

Thus

$$\mathrm{var}\ \theta_* = \frac{\left(\frac{1}{V_B}\right)^2 V_B + \left(\frac{1}{V_W}\right)^2 V_W}{\left(\frac{1}{V_B} + \frac{1}{V_W}\right)^2} = \frac{V_B V_W}{V_B + V_W} \qquad (2.3.2.2)$$

Method 3: Efficient bivariate analysis.

Since $E(y) = A\theta$ and $V(y) = V$, an efficient estimate of

$$\hat{\theta} = \begin{bmatrix} \hat{\theta}_1 \\ \hat{\theta}_2 \end{bmatrix},$$

is given by,

$$\hat{\theta} = (A^T V^{-1} A)^{-1} A^T V^{-1} y \quad ,$$

where A^T is the transpose of matrix A and the suffix -1 denotes the inverse of the matrix. It may be shown that $A^T V^{-1} A$ can be expressed as

$$\begin{bmatrix} \frac{\lambda_2 v_2}{d_B} + \frac{v_2}{d_W} & -\frac{c_B}{d_B} - \frac{c_W}{d_W} \\ -\frac{c_B}{d_B} - \frac{c_W}{d_W} & \frac{\lambda_1 v_1}{d_B} + \frac{v_1}{d_W} \end{bmatrix}$$

where $d_B = \lambda_1 \lambda_2 v_1 v_2 - c_B^2$

$d_W = v_1 v_2 - c_W^2$

$c_B = \rho_B \surd(\lambda_1 \lambda_2 v_1 v_2)$

$c_W = \rho_W \surd(v_1 v_2)$.

The variance matrix

$$V(\hat{\theta}) = \begin{bmatrix} \text{var } \hat{\theta}_1 & \text{cov}(\hat{\theta}_1, \hat{\theta}_2) \\ \text{cov } (\hat{\theta}_1, \hat{\theta}_2) & \text{var } \hat{\theta}_2 \end{bmatrix}$$

is given by the elements of $(A^T V^{-1} A)^{-1}$. Thus

$$\left.\begin{aligned} \operatorname{Var} \hat{\theta}_1 &= \left(\frac{\lambda_1 v_1}{d_B} + \frac{v_1}{d_W}\right) \Big/ \Delta \\ \operatorname{Var} \hat{\theta}_2 &= \left(\frac{\lambda_2 v_2}{d_B} + \frac{v_2}{d_W}\right) \Big/ \Delta \\ \operatorname{Cov} (\hat{\theta}_1, \hat{\theta}_2) &= -\left(-\frac{c_B}{d_B} - \frac{c_W}{d_W}\right) \Big/ \Delta \end{aligned}\right\} \qquad (2.3.2.3)$$

where

$$\Delta = \left(\frac{\lambda_2 v_2}{d_B} + \frac{v_2}{d_W}\right)\left(\frac{\lambda_1 v_1}{d_B} + \frac{v_1}{d_W}\right) - \left(-\frac{c_B}{d_B} - \frac{c_W}{d_W}\right)^2 ,$$

Δ being the determinant of the matrix $A^T V^{-1} A$.

2.3.3 Relative efficiency

The efficiency of the univariate estimators $\tilde{\theta}_1$, $\tilde{\theta}_2$, $\tilde{\theta}_1+\tilde{\theta}_2$ and θ_* may be defined relative to the fully efficient bivariate estimates $\hat{\theta}_1$, $\hat{\theta}_2$, $\hat{\theta}_1+\hat{\theta}_2$, as follows:

Univariate analysis of each cut,

$$E_i \text{ (efficiency of } \tilde{\theta}_i) = \frac{\text{Var } \hat{\theta}_i}{\text{Var } \tilde{\theta}_i} \quad , \ i = 1, 2 \ ; \qquad (2.3.3.1)$$

Sum of univariate cut estimates,

$$E_{1+2} \text{ (efficiency of } \tilde{\theta}_1 + \tilde{\theta}_2)$$

$$= \frac{\text{var } \hat{\theta}_1 + \text{var } \hat{\theta}_2 + 2\text{cov}(\hat{\theta}_1, \hat{\theta}_2)}{\text{var } \tilde{\theta}_1 + \text{var } \tilde{\theta}_2 + 2\text{cov}(\tilde{\theta}_1, \tilde{\theta}_2)} \ ; \qquad (2.3.3.2)$$

Univariate analysis of plot totals,

$$E_* \text{ (efficiency of } \theta_*)$$

$$= \frac{\text{var } \hat{\theta}_1 + \text{var } \hat{\theta}_2 + 2\text{cov}(\hat{\theta}_1, \hat{\theta}_2)}{\text{var } \theta_*} \ . \qquad (2.3.3.3)$$

2.3.4 Specific models

The efficiencies of the univariate estimation methods relative to the fully efficient bivariate method are now examined by means of analysis for the special case where the correlation between cuts is the same between blocks as it is within blocks. Three models from the special case are examined:

$$
\begin{array}{rlll}
\text{Model A}: & \rho_B = \rho_W & ; & \lambda_1 = \lambda_2;\ \ v_1, v_2 \ \text{general}. \\
\text{B}: & \rho_B = \rho_W = 0 & ; & \lambda_1, \lambda_2, v_1, v_2 \ \text{general}. \\
\text{C}: & \rho_B = \rho_W & ; & \lambda_1, \lambda_2, v_1, v_2 \ \text{general}.
\end{array}
$$

Model A: Suppose that the ratio of the between to within block variances is the same in each cut and that the correlations between cuts is the same in each stratum. Substituting $\rho = \rho_B = \rho_W$ and $\lambda = \lambda_1 = \lambda_2$ in (2.3.2.1) and (2.3.2.3) gives:

$$\text{Var } \hat{\theta}_i = \frac{v_i\lambda}{1+\lambda} = \text{Var } \tilde{\theta}_1 \quad ;$$

$$\text{Cov}(\hat{\theta}_1, \hat{\theta}_2) = \frac{\rho\lambda\sqrt{v_1 v_2}}{1+\lambda} = \text{Cov}(\tilde{\theta}_1, \tilde{\theta}_2) \quad ;$$

Substituting in (2.3.2.2),

$$\text{Var } \theta_* = \frac{\lambda(v_1 + v_2 + 2\rho\sqrt{v_1 v_2})}{1+\lambda} \quad ,$$

$$= \text{var}(\hat{\theta}_1 + \hat{\theta}_2) = \text{var}(\tilde{\theta}_1 + \tilde{\theta}_2) \quad .$$

Hence, from (2.3.3.1), (2.3.3.2), and (2.3.3.3), $E_1 = E_2 = E_{1+2} = E_* = 1$. Thus, if the correlation between cuts is the same between blocks as it is within blocks and if the ratio of the between block to within block variances is the same in each cut, then each of the univariate estimators is fully efficient.

Model B: Suppose that the correlation between cuts is zero, both between blocks and within blocks. Substituting for $\rho_B = \rho_W = 0$ in (2.3.2.1) and (2.3.2.3) gives:

$$\text{var}\ \hat{\theta}_1 = \frac{v_1\left(\frac{1}{\lambda_1} + 1\right)}{\left(\frac{1}{\lambda_1}+1\right)\left(\frac{1}{\lambda_1}+1\right)} = \frac{v_1\lambda_1}{(1+\lambda_1)} = \text{var}\ \tilde{\theta}_1$$

$$\text{var}\ \hat{\theta}_2 = \frac{v_2\lambda_2}{1+\lambda_2} = \text{var}\ \tilde{\theta}_2 \qquad (2.3.4.1)$$

$$\text{cov}(\hat{\theta}_1, \hat{\theta}_2) = 0 = \text{Cov}(\tilde{\theta}_1, \tilde{\theta}_2)$$

Hence $E_1 = E_2 = E_{1+2} = 1$.

Thus, if there is no correlation between cuts, either within blocks or between blocks, then the univariate individual cut estimates are fully efficient. The sum of the individual cut estimates is also a fully efficient estimate for totals over cuts.

Since $$\text{var}\ \theta_* = \frac{(v_1 + v_2)(\lambda_1 v_1 + \lambda_2 v_2)}{(1 + \lambda_1)v_1 + (1 + \lambda_2)v_2}$$

and using (2.3.3.3) and (2.3.2.3) it may be shown that E_* is a function of v_1, v_2, λ_1 and λ_2 and is in general not equal to 1. Thus, if there is no correlation between cuts, estimates from a univariate analysis of plot totals are not in general fully efficient.

Model C: Suppose that the correlation between cuts is the same within blocks as it is between blocks, but not necessarily zero. Substituting ρ for ρ_B and ρ_W in (2.3.2.3) gives:

$$\text{var}\ \hat{\theta}_1 = \frac{v_1(1-\rho^2)}{\left(1+\frac{1}{\lambda_1}\right)\left(1-\rho^2\alpha\right)},$$

where $$\alpha = \frac{(1+\sqrt{\lambda_1\lambda_2})^2}{(1+\lambda_1)(1+\lambda_2)}.$$

But $\text{var}\ \tilde{\theta}_1 = \dfrac{v_1}{1+\frac{1}{\lambda_1}}$ from (2.3.2.1).

Hence $\text{var}\ \hat{\theta}_1 = \text{var}\ \tilde{\theta}_1 . E_0$ where

$$E_0 = \frac{(1-\rho^2)}{(1-\rho^2\alpha)}. \qquad (2.3.4.2)$$

Similarly $\text{var}\hat{\theta}_2 = \text{var}\ \tilde{\theta}_2 . E_0$

and $\text{cov}(\hat{\theta}_1,\hat{\theta}_2) = \text{cov}(\tilde{\theta}_1,\tilde{\theta}_2) . E_0$

$$\text{Hence}\quad E_1 = E_2 = E_{1+2} = E_0 . \qquad (2.3.4.3)$$

Thus, if the correlation between cuts is the same within blocks as it is between blocks, then the efficiency of the univariate individual-cut estimates will be the same for each cut and for estimates over cuts which are based on the sum of individual-cut estimates. However, these estimates will not in general be fully efficient.

The results of the three models are summarised in Table 2.4.

Table 2.4: Relative efficiencies in models A,B,C

Model		Efficiencies
A	$\rho_B=\rho_W$; $\lambda_1=\lambda_2$	$E_1=E_2=E_{1+2}=E_*=1$
B	$\rho_B=\rho_W=0$	$E_1=E_2=E_{1+2}=1$
C	$\rho_B=\rho_W$	$E_1=E_2=E_{1+2}$

2.3.5 A general model

The restraint $\rho_B=\rho_W$ in the model of the previous section is now removed. The efficiency of the univariate estimators have been examined by substitutions in the formulae of section 2.3.3 for several values of ρ_B, ρ_W, λ_1, λ_2 and of the ratio v_1 to v_2.

Tables 2.5, 2.6, 2.7 give E_*, E_{1+2} and the minimum of E_1 and E_2 respectively.

In each table the efficiencies follow a similar pattern. Where the weights are the same for each cut (i.e. $\lambda_1=\lambda_2$) then the efficiencies are close to 1 irrespective of the correlations. If the weights differ then the loss of efficiency can be substantial, especially when the correlations are high.

Differences in variances between cuts do not greatly influence E_* except when the weights increase along with the variance: then E_* also increases.

In comparisons between tables, E_{1+2} is greater than E_* for many of the values.

2.3.6 Discussion

A multivariate analysis which takes full account of all variances and covariances within and between strata (i.e. Method 3 of section 2.3.2) is the only completely efficient way of estimating variety contrasts in the lattice analysis of individual cuts and totals over cuts data. However computational methods for such an analysis are not readily available.

The efficiency of the alternative univariate estimators (Methods 1 and 2) depend on the correlations between cuts and on

Table 2.5: Relative efficiency of E_{1+2}
(the sum of individual cut estimates)

			$\lambda_1=1$			$\lambda_1=5$			$\lambda_1=100$		
			λ_2			λ_2			λ_2		
v_1/v_2	P_B	P_W	1	5	100	1	5	100	1	5	100
1.00	0.90	0.90	1.000	0.648	0.369	0.648	1.000	0.702	0.369	0.702	1.000
1.00	0.50	0.50	1.000	0.959	0.882	0.959	1.000	0.968	0.882	0.968	1.000
1.00	0.10	0.10	1.000	0.999	0.996	0.999	1.000	0.999	0.996	0.999	1.000
1.00	-0.50	-0.50	1.000	0.959	0.882	0.959	1.000	0.968	0.882	0.968	1.000
1.00	0.70	0.90	0.997	0.823	0.630	0.823	0.998	0.892	0.630	0.892	1.000
1.00	0.30	0.50	0.995	0.968	0.924	0.968	0.997	0.983	0.924	0.983	1.000
1.00	-0.10	0.10	0.990	0.991	0.994	0.991	0.994	0.998	0.994	0.998	1.000
1.00	0.90	0.10	0.929	0.910	0.798	0.910	0.959	0.872	0.798	0.872	0.997
1.00	0.50	0.30	0.995	0.976	0.927	0.976	0.997	0.977	0.927	0.977	1.000
1.00	0.10	-0.10	0.990	0.991	0.994	0.991	0.994	0.998	0.994	0.998	1.000
10.00	0.90	0.90	1.000	0.648	0.369	0.648	1.000	0.702	0.369	0.702	1.000
10.00	0.50	0.50	1.000	0.959	0.882	0.959	1.000	0.968	0.882	0.968	1.000
10.00	0.10	0.10	1.000	0.999	0.996	0.999	1.000	0.999	0.996	0.999	1.000
10.00	-0.50	-0.50	1.000	0.959	0.882	0.959	1.000	0.968	0.882	0.968	1.000
10.00	0.70	0.90	0.990	0.884	0.699	0.760	0.995	0.914	0.560	0.863	1.000
10.00	0.30	0.50	0.993	0.989	0.955	0.948	0.996	0.991	0.897	0.973	1.000
10.00	-0.10	0.10	0.990	0.991	0.994	0.991	0.994	0.998	0.994	0.998	1.000
10.00	0.90	0.70	0.990	0.710	0.414	0.865	0.992	0.707	0.599	0.812	0.999
10.00	0.50	0.30	0.993	0.950	0.890	0.992	0.996	0.965	0.954	0.988	1.000
10.00	0.10	-0.10	0.990	0.991	0.994	0.991	0.994	0.998	0.994	0.998	1.000
100.00	0.90	0.90	1.000	0.648	0.369	0.648	1.000	0.702	0.369	0.702	1.000
100.00	0.50	0.50	1.000	0.959	0.882	0.959	1.000	0.968	0.882	0.968	1.000
100.00	0.10	0.10	1.000	0.999	0.996	0.999	1.000	0.999	0.996	0.999	1.000
100.00	-0.50	-0.50	1.000	0.959	0.882	0.959	1.000	0.968	0.882	0.968	1.000
100.00	0.70	0.90	0.980	0.912	0.725	0.727	0.991	0.922	0.525	0.845	0.999
100.00	0.30	0.50	0.990	0.996	0.965	0.940	0.995	0.993	0.888	0.968	1.000
100.00	-0.10	0.10	0.990	0.991	0.994	0.991	0.994	0.998	0.994	0.998	1.000
100.00	0.90	0.70	0.980	0.658	0.375	0.892	0.984	0.687	0.637	0.841	0.999
100.00	0.50	0.30	0.990	0.938	0.876	0.996	0.994	0.962	0.961	0.991	1.000
100.00	0.10	-0.10	0.990	0.991	0.994	0.991	0.994	0.998	0.994	0.998	1.000

Key: Efficiency less than 0.85. 🟩

Table 2.6: Relative efficiency of E_*

(the univariate analysis of plot totals)

			$\lambda_1=1$			$\lambda_1=5$			$\lambda_1=100$		
			λ_2			λ_2			λ_2		
v_1/v_2	P_B	P_W	1	5	100	1	5	100	1	5	100
1.00	0.90	0.90	1.000	0.569	0.248	0.569	1.000	0.640	0.248	0.640	1.000
1.00	0.50	0.50	1.000	0.845	0.614	0.845	1.000	0.887	0.614	0.887	1.000
1.00	0.10	0.10	1.000	0.885	0.739	0.885	1.000	0.924	0.739	0.924	1.000
1.00	-0.50	-0.50	1.000	0.887	0.843	0.887	1.000	0.942	0.843	0.942	1.000
1.00	0.70	0.90	1.000	0.719	0.420	0.719	1.000	0.811	0.420	0.811	1.000
1.00	0.30	0.50	1.000	0.846	0.638	0.846	1.000	0.897	0.638	0.897	1.000
1.00	-0.10	0.10	1.000	0.868	0.729	0.868	1.000	0.918	0.729	0.918	1.000
1.00	0.90	0.10	1.000	0.884	0.620	0.884	1.000	0.826	0.620	0.826	1.000
1.00	0.50	0.30	1.000	0.874	0.670	0.874	1.000	0.903	0.670	0.903	1.000
1.00	0.10	-0.10	1.000	0.907	0.787	0.907	1.000	0.938	0.787	0.938	1.000
10.00	0.90	0.90	1.000	0.576	0.221	0.601	1.000	0.635	0.303	0.668	1.000
10.00	0.50	0.50	1.000	0.861	0.528	0.905	1.000	0.876	0.765	0.932	1.000
10.00	0.10	0.10	1.000	0.912	0.597	0.967	1.000	0.908	0.931	0.980	1.000
10.00	-0.50	-0.50	1.000	0.956	0.528	0.999	1.000	0.895	0.985	0.997	1.000
10.00	0.70	0.90	0.991	0.799	0.419	0.698	0.996	0.829	0.458	0.818	1.000
10.00	0.30	0.50	0.995	0.910	0.572	0.884	0.997	0.901	0.775	0.934	1.000
10.00	-0.10	0.10	0.993	0.946	0.596	0.945	0.996	0.914	0.924	0.975	1.000
10.00	0.90	0.70	0.991	0.626	0.248	0.818	0.993	0.638	0.507	0.779	0.999
10.00	0.50	0.30	0.995	0.842	0.533	0.960	0.997	0.872	0.861	0.962	1.000
10.00	0.10	-0.10	0.993	0.887	0.596	0.995	0.996	0.903	0.980	0.995	1.000
100.00	0.90	0.90	1.000	0.611	0.248	0.629	1.000	0.659	0.343	0.689	1.000
100.00	0.50	0.50	1.000	0.920	0.614	0.941	1.000	0.920	0.843	0.956	1.000
100.00	0.10	0.10	1.000	0.979	0.739	0.993	1.000	0.968	0.983	0.995	1.000
100.00	-0.50	-0.50	1.000	0.992	0.843	0.976	1.000	1.000	0.920	0.979	1.000
100.00	0.70	0.90	0.980	0.875	0.498	0.702	0.991	0.873	0.487	0.827	0.999
100.00	0.30	0.50	0.990	0.975	0.698	0.918	0.995	0.956	0.847	0.955	1.000
100.00	-0.10	0.10	0.990	0.999	0.787	0.980	0.995	0.986	0.979	0.992	1.000
100.00	0.90	0.70	0.980	0.615	0.250	0.875	0.984	0.643	0.601	0.828	0.999
100.00	0.50	0.30	0.990	0.890	0.605	0.989	0.994	0.910	0.935	0.984	1.000
100.00	0.10	-0.10	0.990	0.960	0.729	0.998	0.995	0.962	1.000	1.000	1.000

Key: Efficiency less than 0.85. 🟩

Table 2.7: Relative efficiency of the minimum of E_1 and E_2 (univariate analysis of individual cuts)

			$\lambda_1=1$			$\lambda_1=5$			$\lambda_1=100$		
			λ_2			λ_2			λ_2		
v_1/v_2	P_B	P_W	1	5	100	1	5	100	1	5	100
1.00	0.90	0.90	1.000	0.648	0.369	0.648	1.000	0.702	0.369	0.702	1.000
1.00	0.50	0.50	1.000	0.959	0.882	0.959	1.000	0.968	0.882	0.968	1.000
1.00	0.10	0.10	1.000	0.999	0.996	0.999	1.000	0.999	0.996	0.999	1.000
1.00	-0.50	-0.50	1.000	0.959	0.882	0.959	1.000	0.968	0.882	0.968	1.000
1.00	0.70	0.90	0.972	0.709	0.506	0.709	0.988	0.834	0.506	0.834	0.999
1.00	0.30	0.50	0.988	0.937	0.884	0.937	0.994	0.966	0.884	0.966	1.000
1.00	-0.10	0.10	0.990	0.991	0.994	0.991	0.994	0.998	0.994	0.998	1.000
1.00	0.90	0.10	0.787	0.515	0.335	0.515	0.784	0.609	0.335	0.609	0.969
1.00	0.50	0.30	0.988	0.933	0.873	0.933	0.993	0.960	0.873	0.960	0.999
1.00	0.10	-0.10	0.990	0.991	0.994	0.991	0.994	0.998	0.994	0.998	1.000
10.00	0.90	0.90	1.000	0.648	0.369	0.648	1.000	0.702	0.369	0.702	1.000
10.00	0.50	0.50	1.000	0.959	0.882	0.959	1.000	0.968	0.882	0.968	1.000
10.00	0.10	0.10	1.000	0.999	0.996	0.999	1.000	0.999	0.996	0.999	1.000
10.00	-0.50	-0.50	1.000	0.959	0.882	0.959	1.000	0.968	0.882	0.968	1.000
10.00	0.70	0.90	0.972	0.709	0.506	0.709	0.988	0.834	0.506	0.834	0.999
10.00	0.30	0.50	0.988	0.937	0.884	0.937	0.994	0.966	0.884	0.966	1.000
10.00	-0.10	0.10	0.990	0.991	0.994	0.991	0.994	0.998	0.994	0.998	1.000
10.00	0.90	0.70	0.972	0.629	0.362	0.629	0.978	0.679	0.362	0.679	0.998
10.00	0.50	0.30	0.988	0.933	0.873	0.933	0.993	0.960	0.873	0.960	0.999
10.00	0.10	-0.10	0.990	0.991	0.994	0.991	0.994	0.998	0.994	0.998	1.000
100.00	0.90	0.90	1.000	0.648	0.369	0.648	1.000	0.702	0.369	0.702	1.000
100.00	0.50	0.50	1.000	0.959	0.882	0.959	1.000	0.968	0.882	0.968	1.000
100.00	0.10	0.10	1.000	0.999	0.996	0.999	1.000	0.999	0.996	0.999	1.000
100.00	-0.50	-0.50	1.000	0.959	0.882	0.959	1.000	0.968	0.882	0.968	1.000
100.00	0.70	0.90	0.972	0.709	0.506	0.709	0.988	0.834	0.506	0.834	0.999
100.00	0.30	0.50	0.988	0.937	0.884	0.937	0.994	0.966	0.884	0.966	1.000
100.00	-0.10	0.10	0.990	0.991	0.994	0.991	0.994	0.998	0.994	0.998	1.000
100.00	0.90	0.70	0.972	0.629	0.362	0.629	0.978	0.679	0.362	0.679	0.998
100.00	0.50	0.30	0.988	0.933	0.873	0.933	0.993	0.960	0.873	0.960	0.999
100.00	0.10	-0.10	0.990	0.991	0.994	0.991	0.994	0.998	0.994	0.998	1.000

Key: Efficiency less than 0.85. 🟩

the weights given to between and within-block estimates. As shown in the previous section, when the weights differ then the efficiency becomes less than one and decreases further as the correlation between cuts increases.

The univariate estimators are only inefficient if there is inter-block information available. For example, there will not be any inter-block information present when there are no real differences between blocks, i.e. when $\lambda_i=1$. Then $\rho_B=\rho_W$ and, as shown in section 2.3.4, all efficiencies will be 1.

In herbage variety trials real block differences can be expected. From Table 2.1 it will be seen that in past trials the average replicate mean square ranged in size from one to nine times the corresponding residual mean square: the ratio of the mean squares was, on average, four. With smaller blocks in a lattice arrangement the average ratio of block to residual mean squares is likely to be smaller $(1 \leftarrow \lambda_i \leftarrow 4)$. The correlations between cut yields in past herbage trials are shown in Table 2.8. The correlations are low. Corresponding plot and replicate correlations are almost identical $(\rho_B \rightarrow \rho_W)$. This evidence, together with the results of sections 2.3.4 and 2.3.5, suggests that the efficiency of the univariate estimators in the lattice analysis of grass yields will not be less than .8 and should generally be greater than .9.

The choice of univariate estimator may be important. A comparison of Tables 2.5 and 2.6 indicates that a simple sum of individual-cut estimates is broadly a more efficient estimator of total-over-cut yields than a univariate analysis of plot totals.

Table 2.8: Average between-cut correlations per plot and per replicate - data are DM yield in first harvest year of Scottish Colleges trials 1974-78

Plot (and replicate) correlation coefficients

		Cut group			
		1	2	3	4
PRG FREQUENT					
	2	-.51(-.50)			
cut	3	-.03(-.03)	.36(.36)		
group	4	.11(.11)	.12(.12)	.37(.35)	
	Total	.27(.28)	.53(.53)	.78(.78)	.55(.54)
PRG CONSERVATION					
	2	.00(.00)			
cut	3	.04(.04)	.21(.22)		
group	4	.01(.00)	-.01(-.22)	.20(.18)	
	Total	.79(.80)	.48(.47)	.48(.47)	.24(.22)
IRG FREQUENT					
	2	-.02(-.01)			
cut	3	.24(.23)	.45(.44)		
group	4	.25(.25)	.34(.34)	.48(.47)	
	Total	.50(.50)	.70(.70)	.85(.84)	.65(.64)
IRG CONSERVATION					
	2	.17(.19)			
cut	3	.16(.17)	.35(.36)		
group	4	.16(.18)	.16(.16)	.44(.43)	
	Total	.78(.80)	.56(.56)	.61(.60)	.56(.56)

However the former method does not directly provide an estimate of experimental error. For this reason the univariate analysis of totals may be preferred.

The introduction of further cuts, beyond the two considered here, is unlikely to affect conclusions substantially in so far as they apply to herbage variety trials: the bulk of annual herbage yields is taken in one cut; correlations between cuts further apart tend to be small; block differences should diminish as more cuts are taken.

On the evidence here, a procedure can be recommended for the analysis of herbage yield data from lattice experiments as follows:

analyse each cut individually with recovery of inter-block information;

similarly analyse the totals over cuts, if estimates of experimental error are required;

otherwise, sum the estimates from individual cut analyses.

The model of section 2.3.1 is of wider application than just the lattice analysis of herbage trials. It may also be applied to experiments where produce is graded and analyses are required for each grade and for totals, e.g. potato yields. A further use is in over-trials and over-years analysis of multiple harvest data.

CHAPTER 3

BETWEEN-TRIAL VARIATION

3.1 INTRODUCTION

A single trial, however accurately assessed internally, is of limited value in predicting the performance of treatments when applied widely. The results of each trial merges information on variety effects which are general and permanent as well as effects which are a feature of the particular environment associated with the trial. It is only when an experiment is repeated over a range of environments that these effects can be separated.

The separation of environmental and other effects is done by dividing the total variance of all observations into parts associated with each of the effects, i.e. into their variance components.

Variance components are important in variety testing for several reasons: they describe the effects of the main factors which are a permanent influence on the trials system - the subject of this chapter; they are needed in the efficient estimation of variety performance - considered in Chapter 5; they are also useful in determining the optimal allocation of trial resources - Chapter 6.

In this chapter, variance components are used to measure and describe yield variation in official UK herbage trials.

3.2 ESTIMATING COMPONENTS OF VARIANCE

Since new varieties are usually sown for only a few years, the variety x centre x year data matrix is incomplete. Estimating components of variance from such tables has in the past been difficult and the practice has been to avoid the problem by restricting the analysis to complete sets of data.

Techniques have long been available for variance component estimation with simple cross-classifications having equal numbers in each cell. The techniques usually involved computing mean squares in the standard analysis of variance, equating the mean squares to their expectations, and solving for the unknown variance components. This analysis of variance approach was extended to non-orthogonal data matrices by Henderson (1953). The method of Henderson has been widely used in animal genetics work.

While the analysis of variance method provides unbiased estimates, these estimates are not efficient when the data matrix is non-orthogonal. In recent years advances in computing and computational algorithms have made feasible the use of more efficient maximum likelihood methods. Hartley and Rao (1967) outlined a procedure which maximises the likelihood of the complete data matrix. However the method gives estimates which are biased even for balanced data. To overcome this difficulty, Patterson and Thompson (1974) proposed an approach which maximises the likelihood, not of the complete data matrix, but of all contrasts with zero expectation. In this residual maximum likelihood approach, variance estimates reduce in the balanced case to the usual analysis of variance estimates.

Other variance component procedures include those which give estimates with local minimum variance. The relationship between these and maximum likelihood methods has been examined by Harville (1977).

3.3 A MODEL OF THE TRIALS SYSTEM

Several models of the trials system are considered in this thesis. The form of each model is determined in the first instance by the circumstances in which it is to be applied. Here the concern is with measuring the effect of the main factors influencing the trials system.

Experience has shown that apart from variety and management, the major factors affecting yield performance in UK herbage variety trials may be classified under the headings of centre (location) and year (season).

The term 'centre' embraces all of those effects which contribute to making performance at one centre different from that at other centres each year. These effects are primarily associated with soil and husbandry, but some climatic effects may also be involved.

'Year' effects are principally caused by differences in climate but may also be due to variation in disease levels and to changes over seasons in husbandry practices which apply at all centres. In herbage trials 'year' effects are the sum of the influences of the sowing year, the harvest year and any intervening years.

'Year' and 'centre' factors do not act independently. A prolonged period without rain will have different consequences for centres with sandy soil than for those on clay soil. The location of a trial within a centre may change from year to year. Local husbandry practices may also change. All of these effects are represented by a 'centre x year' interaction term.

As well as environmental terms, the model must include a 'variety' term to take account of differences between varieties in their average performance over all environments.

Of most interest here is how the relative performance of varieties changes between environments. Any one environmental factor may not influence relative performance to the same extent as another. Hence separate 'variety x centre', 'variety x year' and 'variety x centre x year' terms are required. The 'variety x centre' component results from the relative performance of varieties changing from centre to centre in a way that is similar each year. The 'variety x year' variance arises from differences in variety performance between seasons which are apparent at all centres. The 'variety x centre x year' term represents variety differences which change from centre to centre to an extent which is dependent on the season, or variety differences which are affected by seasonal changes in some centres more than others.

Two factors that are not incorporated directly in the present model are management and harvest year. Management is excluded since yields under the two systems are required for quite different purposes: instead, results from each management are treated as separate measures. Results for each harvest year are also treated individually so that differences between harvest years in any of the components might be identified.

The terms for 'year' and 'centre' in the model must be viewed as representative rather than random, in the statistical sense. In so far as the sample of years and centres is representative of long-term farming experience, then the interaction of 'year' and 'centre' with each other and with varieties may be considered to be random.

3.4 HERBAGE YIELD VARIATION

Components of variance have been estimated for recent UK herbage trial data, using the model outlined in the previous section and the residual maximum likelihood analysis of Patterson and Thompson (1974). The data examined were trial means for total season dry matter yield from trials sown in the period 1974-78 and harvested during the years 1975-80. The extent of the data is described in Table 3.1.

The estimated variety and environment components for yield are given in Table 3.2. The size of the environment components in Table 3.2 illustrates the dominating influence of those factors which are substantially beyond the control of both experimenter and farmer. The large size of the 'centre x year' component emphasises this point and indicates that the effect of weather on yield is more important locally than in the UK as a whole.

For the species timothy and cocksfoot, frequent management produces a much narrower range of variety performance than does conservation management. It would appear that in these species, more frequent cutting from early growth may reduce differences between varieties.

Large differences in components between harvest years only occur with timothy and cocksfoot frequent management. Differences in the 'centre' component originate from one centre (SH). The 'year' component differences are due to exceptionally low second-year yields in 1976 - a dry season.

Table 3.1: Extent of data used in analysis

	PRG	IRG	TIM	CFT	RCL
			numbers		
VARIETIES	78	34	13	16	26
SOWING YEARS	5	5	5	5	5
CENTRES	11	11	8	7	9
TRIALS	54	54	35	33	37
VARIETY x TRIALS MEANS	1841	834	246	240	403

Table 3.2: Estimated variety and environment components of variance for total season DM yield - UK herbage variety trials sown 1974-78

SPECIES	MAN.	HARVEST YEAR	VARIETY	CENTRE	YEAR	CENTRE x YEAR	MEAN YIELD (tonne/ha)
			component of variance (tonne/ha)^2				
PRG	C	1	.325	.629	1.517	3.249	15.5
		2	.229	1.154	1.472	1.923	12.5
	F	1	.140	.361	.314	2.374	11.5
		2	.218	.497	.666	2.136	9.7
IRG	C	1	.515	3.396	2.389	3.981	15.5
		2	.679	1.730	1.488	3.324	11.9
	F	1	.295	.816	.855	3.344	10.8
		2	.320	.725	.908	2.253	8.9
TIM	C	1	.436	1.080	.509	1.693	12.1
		2	.273	.894	.946	1.722	11.2
	F	1	.053	1.340	.039	.707	9.3
		2	.061	.087	1.379	1.968	8.6
CFT	C	1	.120	1.717	.272	2.864	12.3
		2	.224	.567	.231	2.523	12.2
	F	1	.072	1.807	.165	1.224	10.0
		2	.052	.240	1.326	2.305	10.0
RCL	C	1	.445	3.496	.922	4.413	11.3
		2	.174	1.304	.488	3.335	9.5

There is no consistent pattern between species of variety differences diminishing or increasing in later harvest years.

The variety x environment interaction components are given in Table 3.3. The 'variety x centre x year' and experimental error components are both real and substantial. Each component is much larger in conservation than in frequent management.

The 'variety x centre' and 'variety x year' components are small though not negligible. The size of these components relative to their standard errors suggests that in frequent management it is possible to distinguish real differences between centres in the relative performance of some varieties.

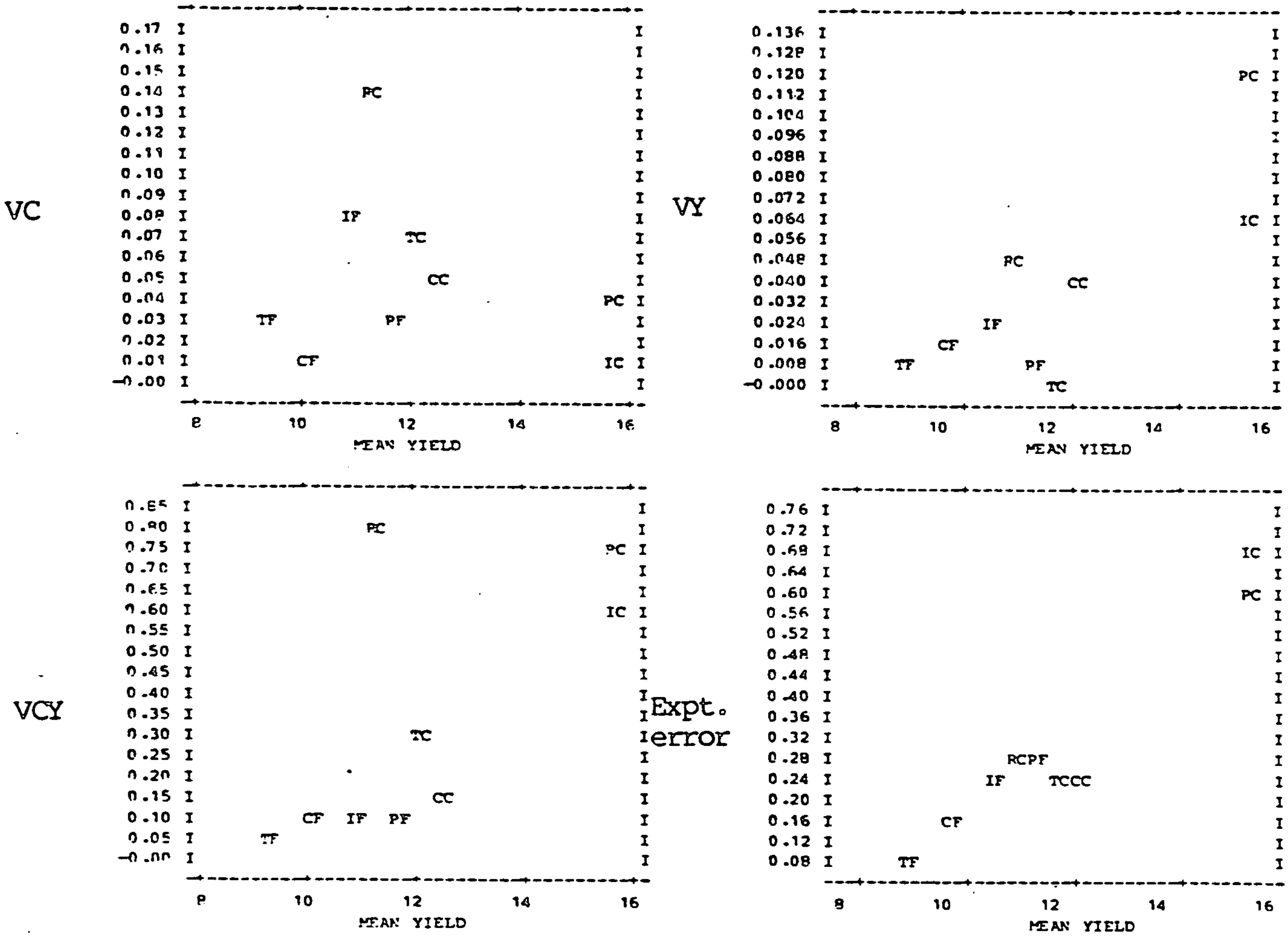
The relationship between each variety x environment component and mean yield of all varieties within a species is shown in Figure 3.1. In general, the size of the 'variety x year', 'variety x centre x year' and experimental error component increases as mean species yield increases. Red clover is an exception but disease affected yields of susceptible red clover varieties at some centres in some years.

The 'variety x centre' term does not show the same relationship with mean species yield as do other terms. It appears that herbage varieties respond to variation between centres in ways that differ from their response to variation from other sources. These differences may be associated with a distinction between the effects of soil and meteorological factors. Differential response to meteorological factors will appear as 'variety x year' and 'variety x centre x year' interactions. Differential response to soil factors will appear as a 'variety x centre' interaction.

Table 3.3: Estimated variety x environment components of variance for total season DM yield (tonne/ha) - UK herbage variety trials sown 1974-78

SPECIES	MAN.	HARVEST YEAR	VARIETY x CENTRE	VARIETY x YEAR	VARIETY x CENTRE x YEAR	EXPT. ERROR	CV %
			component of variance (standard error)				
PRG	C	1	.036(.032)	.118(.032)	.745(.048)	.618	5.1
		2	.012(.026)	.246(.050)	.625(.040)	.422	5.2
	F	1	.029(.008)	.008(.005)	.114(.011)	.262	4.4
		2	.034(.007)	.009(.004)	.039(.008)	.236	5.0
IRG	C	1	.006(.044)	.064(.035)	.623(.068)	.699	5.4
		2	.034(.048)	.158(.062)	.586(.066)	.454	5.6
	F	1	.081(.016)	.023(.010)	.092(.016)	.252	4.7
		2	.065(.020)	.027(.014)	.129(.020)	.213	5.2
TIM	C	1	.071(.048)	.004(.022)	.276(.052)	.250	4.1
		2	.024(.036)	.027(.032)	.190(.051)	.294	4.8
	F	1	.030(.015)	.008(.009)	.047(.016)	.097	3.4
		2	.032(.018)	.000(.008)	.051(.018)	.135	4.3
CFT	C	1	.053(.037)	.037(.031)	.140(.042)	.254	4.1
		2	.143(.107)	.010(.042)	.334(.084)	.321	4.7
	F	1	.013(.019)	.019(.016)	.094(.025)	.154	3.9
		2	.056(.026)	.025(.019)	.067(.023)	.146	3.8
RCL	C	1	.144(.090)	.048(.056)	.812(.110)	.296	4.8
		2	.478(.176)	.034(.079)	1.168(.176)	.270	5.5

Figure 3.1: Relationship between variety x environment variances and mean species yield - data are total season DM yield from first harvest year of UK herbage trials 1974-78.



KEY:
VC - variety x centre variance component $(\text{tonne/ha})^2$
VY - variety x year
VCY - variety x centre x year
Expt. error - variance between plots within trials
PC (PF) - PRG C management (PRG F management)
IC (IF) - IRG
TC (TF) - TIM
CC (CF) - CFT
RC - RCL
MEAN YIELD - DM yield (tonne/ha) averaged over all varieties

Aspects of the 'variety x centre' interaction are examined in the next chapter.

Table 3.4 summarises the contribution of several environmental factors to the accuracy with which a single trial predicts future national yield performance of herbage varieties. Experimental error and year-to-year variation at a centre contribute most to variance estimates from a single trial (but not from a series of trials - see Chapter 6). A similar pattern is noted in UK cereal variety trials as reported by Patterson et al. (1977). However herbage differs from cereals in having a smaller 'variety x year' contribution. Thus a lesser proportion of the variation in herbage trials is due to seasonal effects which are common to all centres.

Table 3.4: Contribution of variance components to accuracy with which a single trial estimates average national performance

MEASURE	MEAN %CONTRIBUTION TO TOTAL VARIANCE				TOTAL VARIANCE (tonne/ha)^2
	VARIETY x CENTRE	VARIETY x YEAR	VARIETY x CENTRE x YEAR	EXPT. ERROR	
DM herbage yield (i)					
CONS.	9	6	58	27	.847
FREQ.	16	6	38	40	.235
DM cereal grain yield (ii)	13	13	46	28	.166

Note: (i) First harvest year total season DM yield for PRG, IRG, TIM, CFT, RCL.

(ii) Grain yield from barley, oat and wheat trials in UK as reported by Patterson et al. (1977).

3.5 DISCUSSION

The results of the previous section demonstrate how total season yield of herbage varieties varies most when varieties are less frequently cut - that is under conservation management. It appears also that the greater variation under conservation management is primarily associated with meteorological factors. Although varieties are less variable under frequent management, it is nevertheless possible to distinguish real differences between centres in the relative performance of varieties.

The estimated variances of section 3.4 are averages. Inevitably some varieties will vary far more than others, either generally or in response to changes in specific types of environment, e.g. seasons. Thus while the components describe what happens on average the variation of individual varieties may be substantially different. Some aspects of individual variety variability are considered in the next chapter.

CHAPTER 4

SPECIFIC VARIETY X ENVIRONMENT VARIATION

4.1 INTRODUCTION

Varieties, like individuals, have many features in common. These features can affect the way in which varieties react to environmental influences. Some of the features of herbage varieties which are studied here include time of maturity, ploidy (i.e. chromosome structure), and country of origin.

The previous chapter was concerned with averages of variances of many variety contrasts over several environmental influences. In the present chapter we concentrate on a number of specific variety contrasts. The effects of environment on variability within groups of varieties are described. A between-groups comparison is made of how individual varieties vary over-trials within years. The extent to which this variation can be explained by regression on trial means is explored. The relationship between mean variety yield and variety variability is examined. Finally, we investigate similarities between centres in variety response.

4.2 VARIETY GROUP VARIABILITY

In herbage variety testing, normal practice is to concentrate on comparisons between varieties with similar times of maturing. There are several statistical reasons for this policy: differences between maturity-groups may be much larger than amongst individuals within groups; the variation within some groups may differ from that within others. Since a maturity-group x environment interaction is to be expected, we concentrate here on comparing within-group variation.

Table 4.1 gives within-maturity group components of variance for perennial ryegrass in its first harvest year. Under conservation management, the relative performance of intermediate maturing varieties is more susceptible to centre differences and to seasonal factors which affect all centres than are either the early or late maturing varieties. Against this, early maturing varieties are influenced much more by factors that depend on a combination of season and centre. Under frequent management, differences in components between maturity groups are generally small. From these results it would seem that the procedure of analysing data from conservation management on a within-maturity basis is justified.

Table 4.1 also gives components of variance for varieties grouped by ploidy. There is no evidence here of substantial differences between groups in respect of within-group variability. However, the 'variety x centre x year' component for tetraploids is somewhat larger than that for diploids. This aspect is examined further in the next section.

Many varieties in official herbage trials are bred outside the UK. It is reasonable to ask if imported varieties are more variable than locally bred varieties. Results in Table 4.1 suggest that UK-bred varieties are at least as variable as those from other countries.

Table 4.1: Variances within groups of varieties
- PRG first harvest year total season DM yield (tonne/ha)

MANAG.	GROUP	COMPONENTS OF VARIANCE				NO. OF VARIETIES
		VARIETY	VARIETY X CENTRE	VARIETY X YEAR	VARIETY X CENTRE X YEAR	
	<u>MATURITY</u>		Variance (standard error)			
C	Early	.484	.000(.042)	.000(.023)	.631 (.070)	26
	Inter.	.244	.126(.051)	.150(.059)	.384 (.060)	29
	Late	.113	.052(.044)	.002(.020)	.342 (.060)	23
F	Early	.131	.015(.012)	.007(.007)	.102 (.018)	26
	Inter.	.175	.040(.016)	.007(.008)	.095 (.019)	29
	Late	.093	.000(.014)	.000(.007)	.124 (.023)	23
	<u>PLOIDY</u>					
C	Diploid	.336	.045(.033)	.122(.035)	.622 (.048)	63
	Tetraploid	.168	.000(.077)	.081(.067)	.837 (.123)	15
F	Diploid	.124	.018(.009)	.003(.004)	.116 (.013)	63
	Tetraploid	.210	.047(.017)	.030(.016)	.030 (.018)	15
	<u>ORIGIN</u>					
C	UK	.466	.019(.078)	.185(.106)	.756 (.121)	13
	Netherlands	.244	.019(.044)	.094(.043)	.733 (.071)	34
	Germany	.497	.007(.106)	.069(.083)	.553 (.144)	11
	Denmark	.102	.185(.099)	.173(.110)	.418 (.106)	15
F	UK	.236	.010(.020)	.005(.001)	.139 (.030)	13
	Netherlands	.046	.029(.012)	.003(.006)	.106 (.016)	34
	Germany	.128	.014(.028)	.000(.011)	.083 (.035)	11
	Denmark	.065	.012(.022)	.000(.009)	.075 (.028)	15

4.3 INDIVIDUAL VARIETY VARIABILITY

(i) Variability estimation techniques

Many techniques have been developed to measure and describe individual variety variability. Their number reflect the importance of the subject. The methods have two basic forms: variance measures and regression measures.

The simplest variety variance measure is the variance of a variety's yield from one environment to another. An extension of this is the variance over environments of the difference between a variety and one or more other varieties. More complex measures include those which partition a variety x environment interaction term into components representing the contribution of each variety to the interaction term.

The regression approach to examining variety variability was suggested by Yates and Cochran (1938). They showed how the difference between the yield of one variety and the mean yield of all varieties within a trial may increase or decrease across trials as trial yields increase. They calculated, for each variety, a regression of its yield on trial means. Finlay and Wilkinson (1963) postulated that the regression coefficients represented a measure of variety sensitivity: they suggested that varieties with high coefficients are sensitive to environmental change, while those with low values resist change. Since Finlay and Wilkinson's paper, much work has been done in developing the regression method for analysing interactions (see Freeman (1973) for a detailed review), and in applying it, particularly in plant breeding (see Hill (1975) for a review).

Regression and variance measures of sensitivity are closely related. The nature of this relationship can be seen in a formulation of the bivariate linear regression coefficient estimator

$$b_{yx} = r_{yx} s_y / s_x \quad , \qquad (4.2.1)$$

where s_y is the standard deviation of an individual variety's yields, s_x is the standard deviation of the corresponding trial means, and r_{yx} is the coefficient of correlation between y and x. Thus, a sensitivity coefficient measures two aspects of variety performance. It measures the ratio of the variety's variation to that of the variation between trial means. It also measures how closely this ratio is maintained across environments. It will be apparent from the expression (4.2.1) that a variety will have high sensitivity when r_{yx} approaches 1 and when s_y is greater than s_x. In these circumstances, the variety will perform relatively better than other varieties in high yielding trials. However, low sensitivity does not necessarily mean that a variety will perform relatively better in low yielding trials or, indeed, that s_y is less than s_x. It may indicate that the variety's yields are poorly correlated with those of the trial means.

(ii) Variability of PRG varieties

Differences in herbage variety variability are now examined.

The first two columns of Table 4.2 give estimates of variety variability within groups of PRG varieties. Values in the first

Table 4.2: Individual variety variation
- PRG first harvest year total season DM yield (tonne/ha)

	MEAN LOG STANDARD DEVIATION (i)		AVERAGE SENSITIVITY COEFFICIENT		NO. OF VARIETIES
MANAGEMENT GROUP	C	F	C	F	
<u>Maturity</u>					
Early	1.03	.69	.97	.95	26
Inter.	.97	.69	1.06	1.02	29
Late	.98	.71	.99	1.04	23
SE of diff.-min.	.030	.024	.048	.028	
-max.	.033	.027	.054	.031	
<u>Ploidy</u>					
Diploid	.98	.69	.97	1.00	63
Tetraploid	1.06	.70	1.16	1.03	15
SE of diff.	.032	.026	.049	.032	
<u>Origin</u>					
UK	1.01	.71	.96	.96	13
Netherlands	1.00	.69	1.02	1.04	34
Germany	.95	.66	.96	.96	11
Denmark	.98	.70	1.01	1.03	15
SE of diff.-min.	.027	.021	.041	.027	
-max.	.048	.037	.072	.047	

Note: (i) A constant $\log_e 10$ has been added to the transformed standard deviations to give positive numbers in the table.

two columns are the mean of the logarithms of the standard deviations over all varieties in the group. A standard deviation measures the distribution of a variety's effects over centres within years.

The results in Table 4.2 confirm that early varieties tend to be more variable under conservation management. Also, the greater variability of tetraploid varieties is apparent.

(iii) Sensitivity of PRG varieties

Differences in variability may be a consequence of some varieties being more sensitive than others, e.g. doing better in high yielding conditions.

The mean sensitivities of perennial ryegrass varieties are shown in the second two columns of Table 4.2. A value in these columns is the mean of the sensitivity coefficients of varieties in the group. The coefficient for each variety has been calculated by regressing its yield on the adjusted centre-within-year effects.

In Table 4.2 a coefficient greater than 1 indicates above average sensitivity to environmental change, while a coefficient less than 1 identifies below average sensitivity. It should be emphasised that sensitivity is a relative measure and has meaning only in the context of the varieties included in the analysis. Thus, if one group is more sensitive, then another group must be less sensitive.

The coefficients in Table 4.2 indicate that the greater variability of early maturing varieties under conservation management cannot be attributed to above average sensitivity.

Under frequent management, late varieties tend to be more sensitive than early varieties.

It is clear from Table 4.2 that there are real differences in sensitivity between ploidy groups. Tetraploid varieties, in general, respond markedly better to high-yielding conditions, at least under conservation management.

The sensitivity coefficients for varieties grouped by country of origin indicate that, although Dutch varieties are as variable as UK varieties, more of the variability of the former can be attributed to a tendency to perform better in trials with high yields. Also, German-bred varieties are both less variable and more resistant to environmental change.

The results in Table 4.2 emphasise that variability and sensitivity reflect different aspects of variety performance. It will be apparent that both measures are needed to describe variation in individual variety performance.

(iv) Herbage variety sensitivity

Variety sensitivity in each of the five species is examined.

Table 4.3 gives the average proportion of the 'variety x centre' and 'variety x centre x year' variation that is explained by differential sensitivity. In general, the percentage variation is no greater than may be expected from extracting one degree of freedom at random from trial-to-trial variation. In timothy and cocksfoot the percentages for average variation between centres are much larger. These percentages have to be treated with some caution however, since they are directly associated with low yields

Table 4.3: Proportion of variety variation explained by regression on trial means - total season DM yield in first harvest year

SPECIES	MANAGEMENT	VARIATION BETWEEN CENTRES: AVERAGE OVER YEARS	VARIATION BETWEEN CENTRES: POOLED WITHIN YEARS
		% variation due to sensitivity coefficient (number of trials)	
PRG	C	9 (11)	5 (22)
	F	8 (11)	6 (22)
IRG	C	7 (11)	5 (22)
	F	8 (11)	5 (22)
TIM	C	28 (8)	3 (12)
	F	32 (8)	4 (12)
CFT	C	28 (7)	7 (12)
	F	32 (7)	5 (12)
RCL	C	16 (9)	11 (14)

at one centre (SH) for which data are available for only two (timothy) or three (cocksfoot) of the five sowing years. In red clover the relatively large percentages appear to reflect real differences in sensitivity.

Care is needed in the interpretation of sensitivity coefficients. For timothy and cocksfoot, it may well be that some varieties will perform relatively better under low fertility conditions as provided, for example, by centre SH. However, another explanation is that some varieties are suited to particular aspects of SH conditions, not necessarily associated with general level of yields.

(v) Variability and variety yields

An association between mean species yield and increasing variability was noted in Chapter 3. The extent of the association between individual variety yields and variety variability is described in Table 4.4. The table shows the coefficients of correlation between mean variety yields and variety variability. The coefficients are generally small. Perennial ryegrass conservation management is an exception. The reason is that early maturing varieties, which, as has been seen, are more variable, also tend to be higher yielding. The negative correlation in Italian ryegrass conservation management is similarly related to maturity. Here, intermediate maturing varieties are less variable and are also generally higher yielding.

Table 4.4: Relationship between variety mean yield and variability

SPECIES	MANAGEMENT	VARIATION BETWEEN CENTRES: AVERAGE OVER YEARS	VARIATION BETWEEN CENTRES: POOLED WITHIN YEARS	NO. OF VARIETIES
		Coefficient of correlation between yield and standard deviation		
PRG	C	.194	.320 **	74
	F	-.068	-.080	75
IRG	C	-.178	-.442 *	34
	F	-.161	-.071	34
TIM	C	.338	.310	13
	F	-.340	-.065	13
CFT	C	.225	.207	16
	F	-.130	.044	16
RCL	C	-.196	-.124	25

** $P \leq .01$
* $P \leq .05$

4.4 BETWEEN CENTRE ASSOCIATION

Herbage variety trial centres are dispersed widely throughout the UK. Nevertheless, it is inevitable that those environmental conditions which influence relative variety performance are common to several centres.

To examine the similarity between centres in the relative performance of varieties, a principal coordinate analysis was carried out on data for first harvest years total season DM yield from each species. The analysis was done by calculating, for each centre, over-years variety means, using the technique of fitting constants (Chapter 5). A between-centres association matrix was then derived (following Gower (1966)), from the residuals of the resulting variety x centre table with both variety and centre effects removed. Table 4.5 shows the first two latent vectors derived from analysis of the association matrix.

From Table 4.5 it is apparent that there is a similarity in latent vector values between conservation and frequent management within each species: this occurs even though one management is very different from the other in both timing of cuts and yield produced.

It is apparent also from Table 4.5 that relative variety performance at the SH centre is substantially dissimilar from that at other centres in each species. The dissimilarity is illustrated for perennial and Italian ryegrass by plots in Figure 4.1. In timothy and cocksfoot the first coordinate appears to be almost wholly devoted to representing the distance between SH and the other centres. Re-analysis, with SH results omitted,

Table 4.5: Similarity between centres in mean over-years variety performance for first harvest year total season DM yield

	PRG		IRG		TIM		CFT		RLC
CENTRE	C	F	C	F	C	F	C	F	C
				First principal coordinate-latent vector					
CA	.1	.1	-.3	.2	-.0	.4	.1	.2	.3
CP	-.4	-.0	-.4	.4	.1	-.4	-.1	.2	.1
SH	-.1	-.6	.9	-.8	1.1	1.0	1.0	.7	.2
TR	.1	.4	.2	.1	-.1	.0	-.3	-.3	-.3
HA	.2	.4	-.3	-.2					
HH	.2	.5	-.4	.5					
SP	.6	.1	-.0	-.5					.6
ES	-.2	.2	-.1	.3	-.3	-.2	-.2	-.6	-.3
NS	-.1	-.3	.3	-.3	-.0	-.2	-.3	-.0	.3
WS	-.7	-.6	-.1	.5	-.3	-.3			-.8
NI	.3	-.3	.2	-.1	-.3	-.3	-.2	-.1	-.1
%Variance in latent root	26	28	34	50	67	50	47	50	45
				Second principal coordinate-latent vector					
CA	-.0	.3	.2	-.2	-.4	-.5	.8	-.3	-.0
CP	-.5	.3	-.2	-.0	.1	.2	.1	.1	-.1
SH	.6	.2	-.2	-.4	.1	.4	-.2	-.2	-.5
TR	.1	-.1	-.0	.1	-.3	-.2	-.3	.3	.3
HA	.1	.1	-.2	-.1					
HH	-.1	.1	.1	-.2					
SP	-.1	.1	.5	.1					-.0
ES	.2	-.7	-.3	-.1	.1	.1	-.5	-.4	-.1
NS	-.3	-.0	.2	.3	-.0	-.2	-.0	.3	.7
WS	.1	-.2	-.4	.2	.3	-.1			-.1
NI	.0	-.2	.2	.3	.1	.3	.1	.2	-.1
%Variance in latent root	16	15	17	13	17	22	32	26	27

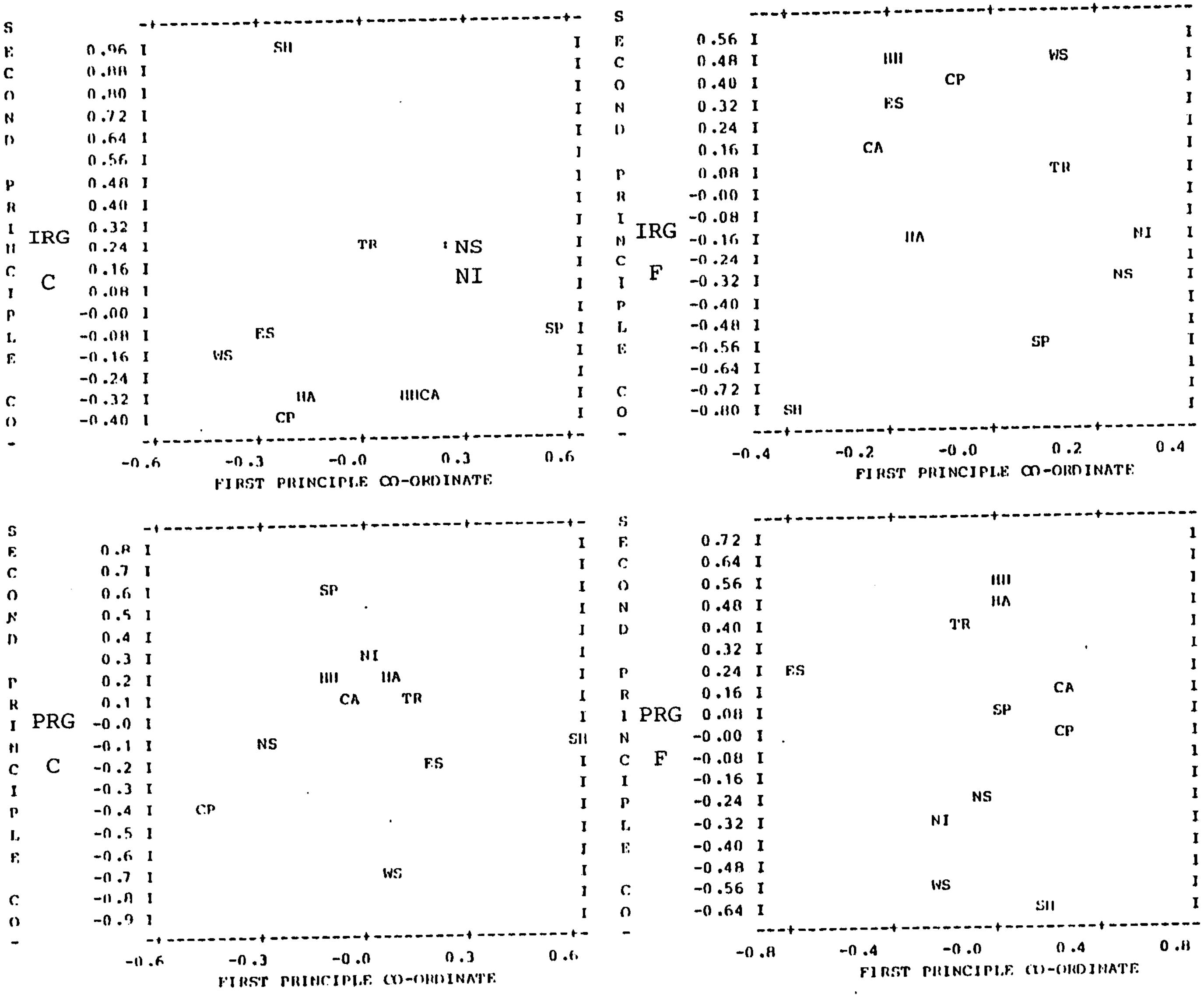


Figure 4.1: Principal coordinate plot showing relative distances between centres for PRG and IRG C and F management, first harvest year total season DM yield.

effectively breaks the association between conservation and frequent management in timothy and cocksfoot but strengthens it in perennial and Italian ryegrass (Table 4.6).

The relationship between latent vectors that occurs across managements, and to some extent across species, suggests that some of the coordinates may be linked with specific environmental factors. In perennial ryegrass there is evidence to suggest a north-south axis. This conflicts with a view that differences between centres may change most in an east-west direction, as determined by rainfall.

It has not been possible to obtain the information on centre characteristics which would allow a detailed study of links between centres to be done in the present investigation. This aspect would appear to merit further work.

Table 4.6: Similarity between centres in mean over-years variety performance (analyses excluding data for SH centre)

	PRG		IRG		TIM		CFT		RCL
CENTRE	C	F	C	F	C	F	C	F	C
				First principal coordinate-latent vector					
CA	.1	.2	-.1	-.2	.7	-.9	.9	-.1	.3
CP	-.4	-.2	-.5	-.4	-.0	.4	-.1	-.4	.1
SH									
TR	.1	.1	.4	.0	.5	-.2	-.3	-.1	-.3
HA	.2	.5	-.4	.3					
HH	.2	.6	-.2	-.6					
SP	.6	.2	.5	.8					.6
ES	-.2	-.0	-.2	-.4	-.3	.2	-.5	1.0	-.3
NS	-.1	-.3	.5	.5	.1	-.1	-.0	-.2	.4
WS	-.7	-.7	-.4	-.4	-.6	.2			-.8
NI	.3	-.4	.5	.3	-.4	.5	-.0	-.2	-.1
%Variance in latent root	30	26	27	47	46	49	53	47	50
				Second principal coordinate-latent vector					
CA	-.0	.4	.6	.3	.1	-.1	.0	.8	.3
CP	-.5	.1	.1	.1	-.6	.2	-.5	.1	.2
SH									
TR	-.1	-.7	-.5	-.1	.1	.4	.2	-.3	-.3
HA	.3	-.0	.1	.1					
HH	.0	-.3	.4	.1					
SP	-.0	.2	.4	.1					.2
ES	.4	.6	-.4	.2	.3	-.2	.0	-.1	.1
NS	-.2	-.0	-.1	.1	-.3	-.2	.4	-.3	-.6
WS	.2	-.1	-.4	-.4	-.2	.3			.0
NI	-.1	-.2	-.1	-.4	.5	-.4	-.1	-.2	.2
%Variance in latent root	16	19	19	13	30	17	19	32	23

CHAPTER 5

VARIETY SELECTION AND ESTIMATION OF FUTURE PERFORMANCE

5.1 INTRODUCTION

Official herbage variety testing in the UK performs two functions: the selection of varieties and the estimation of their future commercial performance. The two functions are closely related and, indeed, are treated as one in practice. Nevertheless they are separate, and may at times conflict, as will be indicated.

5.2 SELECTION

Selection of varieties is done at three distinct stages in official testing: in adding to the NL; including in the RL; and removing from the RL. Attention is concentrated here on selection at the NL stage where there are many candidate varieties and where the quasi-legal nature of the decision process requires the use of criteria that are as objective as possible.

A new herbage variety is accepted on to the NL if its mean performance in official trials reaches the standards set for each of the major characters by which the species is assessed. Standards are set by specifying a control variety and a performance level relative to that control which the candidate must achieve.

The same varieties serve as controls from year to year. However the relative performance level is revised (generally upwards) each year. In doing so, no account is taken of movements in the control between years. The success of a candidate, therefore, relies to some degree on the reaction of another variety to the seasons during which the candidate was in trial.

Herbage varieties are assessed on five characters. These include yield in the first and second harvest years of each management and also persistency (i.e. proportion of the ground that is covered by the species) after the second harvest year.

The selection procedure, as presently applied, requires that a variety achieve the standard on each character. However, the statutory regulations state that, "the qualities of the plant variety shall ... be taken as a whole and inferiority in respect of certain characteristics may be offset by other favourable characteristics". In practice the 'all-or-none' procedure described above is not applied rigorously. Candidates which just fail to meet the standards are examined individually. For these varieties compensation between characters is taken into the selection procedure by ad hoc and subjective weighting of the various features.

There would seem to be no statistical reason why criteria cannot be developed which would permit compensation between characters on an objective basis. Ideally the criteria should be based on a function which took account of the relative utility of gain on some characters weighed against loss on others. It is unlikely that such a utility function would be of a simple linear form, since there will be a limit beyond which gain on one character cannot compensate for proportional losses on other characters. Also the five characters are not functionally independent: second year yields and persistency contain elements of each other. Nevertheless improvements on the present procedure should be possible.

We examine briefly how the present selection procedure operates. Table 5.1 gives the estimated proportion of varieties which, though having higher yields than the standard, will be rejected as a consequence of sampling and experimental errors in trials. The estimates in Table 5.1 are calculated using the components of variance in Table 3.3 and using also between-character error correlations derived from a variety x trials analysis the results of which are given in Table 5.2. In the simulations the distribution of the error variances was assumed to be normal.

From Table 5.1 it may be seen that approximately 1 in 5 of perennial ryegrass, Italian ryegrass and red clover varieties, with yields 5% above the standard on each character will be rejected, if present criteria are strictly applied. For timothy and cocksfoot, a high degree of discrimination is possible.

It must be emphasised that these results do not show the proportion of varieties which will be rejected in practice. The actual proportion will depend on the levels which are set as the standards. However, Table 5.1 can be used to guide in specifying these standards. For example, it may be necessary to ensure that only a few varieties with yields greater than those of a control variety will be rejected. Then, clearly, a standard of 105% of the control would be inadequate for perennial ryegrass, Italian ryegrass and red clover, but might be satisfactory for timothy and cocksfoot.

Table 5.1: Efficiency of present selection criteria

Estimated probability (%) of variety being rejected when true yields are greater than standard on each of four yield characters

True yield as % of standard	PRG	IRG	TIM	CFT	RCL
			Probability(%)		
102.5	47	52	26	35	44
105.0	18	16	2	4	22

Table 5.2: Correlations between harvest year and management in residuals from variety x trials analysis of total season DM yield

Management			C		F
	Harvest		1	2	1
		Species			
C	2	PRG	.18		
		IRG	.20		
		TIM	.34		
		CFT	.15		
		RCL	.31		
F	1	PRG	.12	.10	
		IRG	.18	.08	
		TIM	.21	-.08	
		CFT	.36	.22	
		RCL	-	-	
	2	PRG	.04	.15	.33
		IRG	.07	.22	.38
		TIM	.19	.16	.39
		CFT	.22	.44	.32
		RCL	-	-	-

5.3 ESTIMATION

The accuracy with which trial results predict future performance of varieties is determined principally by the sample of trials available and by the estimating procedure.

5.3.1 Sample of trials

Ideally the trials should be a random selection from those conditions to which future recommendations will apply. In practice, this is not possible. The sample of seasons can only be the most recent of those provided by nature. The trial centres are at best representative of general farming experience. Inevitably, departures from random selection introduce a degree of unquantifiable uncertainty into estimates of future performance.

To some extent, inadequacies in the sample of years may be compensated for by variability in meteorological conditions between centres within years. F. Yates spoke of this in the discussion following Patterson and Silvey's (1980) paper. It is a view which would seem to be supported by Table 3.3 and Figure 3.1, where the 'variety x year' and 'variety x centre x year' components vary across species in a similar manner.

Weaknesses in the sample of trial sites cannot be easily overcome. Trials might be moved to different trial centres each year. However, any gains in accuracy have to be weighed against the additional cost of operating a more widely dispersed trials programme. None the less, choice of sites must be given careful consideration, especially when trials are few. The importance of this aspect is emphasised in the present study by the large contribution made by one centre to the 'variety x centre' component.

5.3.2 The problem of estimation

If all varieties occur in all trials then estimating future variety performance is straightforward. Simple means, or weighted means with all varieties within a trial being given equal weight, provide the most accurate estimates. In practice, it is simple means that are used for NL decisions, since both the control and candidate variety occur in each trial.

In RL work, because varieties are kept in trials for only a few years, an analysis which compares recommended and candidate varieties has to use data from trials extending over ten years and grown at three to seven sites each year. Thus, many of the tables for analysis are similar to that shown in Figure 1.9.

Patterson and Silvey (1980) carried out a thorough review of the methods, i.e. models and associated analysis procedures, for use in estimating mean variety performance. In their paper Patterson and Silvey defined a very general method. They went on to describe several specific methods and showed how these are related to the general method. Three of their specific methods are examined here: fitting constants; augmented fitting constants; and a fully efficient analysis.

5.3.3 Available estimation procedures

Fitting constants is the method currently used for routine estimation of variety means in herbage variety testing. It involves estimating parameters of a model

$$E(y_{ij}) = \alpha_i + C_j \qquad (5.3.1)$$

where y_{ij} is the mean yield of variety i in trial j ; α_i is the mean for variety i averaged over all trials; and C_j is the jth trial effect. The parameters of the model are estimated by minimising an unweighted sum of squares of $y_{ij} - E(y_{ij})$.

Augmented fitting constants, as the name implies, requires the fitting of an extra parameter to equation (5.3.1). The modified equation is,

$$E(y_{ij}) = \alpha_i + \beta_i C_j \qquad (5.3.2)$$

where β_i is a measure of variety sensitivity (Chapter 4).

The efficient method takes account of the stratification of trials by centres and by years. In this approach, a weighted sum of squares of $y_{ij} - E(y_{ij})$ is minimised using separate weights derived from estimates of the 'variety x centre', 'variety x year' and 'variety x centre x year' variances.

Simple fitting constants can be applied in several ways. A one-stage method ignores the year and centre classification and minimises a variety x trials-over-centres-and-years variance.

A two-stage procedure first estimates variety means for each year using fitting constants where necessary: at the second stage constants are fitted (unweighted) to a 'variety x year' table to give variety mean estimates.

Patterson (1978) showed that the two-stage method can be more efficient when the 'variety x year' variance is moderately large, and when each variety occurs in a reasonable number of trials each year. In herbage variety testing, the 'variety x year' term is not large (Table 3.4). Also, the number of centres can be as few as three. In practice, it is single-stage fitting constants which is used for routine estimation of variety means.

Augmented fitting constants serves two roles as has been outlined by Patterson and Silvey (1980). It provides estimates of variety sensitivity. It can also give generally improved estimates of variety means, since in the calculations weights are given to the environmental effects in proportion to the ability of the variety to express itself in the environment.

Because of computational complexities, the efficient method cannot yet be implemented as a routine procedure. However, it is used in special investigations to establish long-term average variances as described in Chapter 3.

5.3.4 An example

Features of those estimators which have been described in the previous section are now examined using as an example some of the data in Figure 1.9.

Table 5.3 summarises five years of trials with ten varieties. The first variety RVP is a control variety and was sown in all trials. The next six varieties are candidate varieties whose mean performance relative to RVP and to each other is to be estimated. The remaining three varieties were also in trials during the

Table 5.3: Variety mean yields - IRG C management - first harvest year total season DM yield (tonne/ha)

	HARVEST YEAR				
VARIETY	1975	1976	1977	1978	1979
	Variety mean yield (tonne/ha)				
RVP	15.5	12.5	18.6	17.5	17.5
ASTOR	14.8	11.8	-	-	-
LIPO	-	12.6	18.4	-	-
WILO	-	12.6	17.7	-	-
MULTIMO	-	-	-	17.4	17.0
TITANIA	-	-	-	16.8	15.8
TOLMAN	-	-	-	16.4	16.1
TETILA	14.9	12.2	17.3	16.4	15.3
ELMET	14.6	-	15.7	-	-
ADRET	-	12.2	-	15.9	-
No. of trials	6	7	7	7	7

period, but are no longer of interest. In practice, these varieties would be excluded from the estimation procedure. They are introduced here to illustrate several points.

The results of analyses of data for seven varieties are given in the first four columns of Table 5.4. The fitting constants and efficient methods produce very similar means. In this example, the 'variety x year' variance is small. As a consequence, differences in the weights assigned within and between years are negligible. In general, when differences in weights do occur then the efficient estimates will lie between the one- and two-stage estimates.

The means produced by augmented fitting constants show the largest differences from the efficient method. The varieties ASTOR and TITANIA are particularly affected as they show the greatest departures from average sensitivity in these data.

Results from analyses with all ten varieties are also given in Table 5.4. As before, the discrepancies between efficient and fitting constants methods are small for most varieties. The augmented fitting constants estimates are now closer to the other estimates. The largest differences in Table 5.4 occur between the analyses with and without the extra varieties. These differences affect the ranking of variety means (Table 5.5). The reason for the differences may be deduced from Table 5.6 which shows the residuals from a 'variety x year' table. RVP performed less well in 1975 and 1976 (drier seasons) than in subsequent years. Since in the smaller data set RVP is the principal link between environments, varieties which happen to be in trials only in those able 5.4: Comparison of methods for estimating variety means

	ANALYSIS WITH 7 VARIETIES				ANALYSIS WITH 10 VARIETIES			
	EFFIC.	ONE STAGE	TWO STAGE	AUGM. FITCON	EFFIC.	ONE STAGE	TWO STAGE	AUGM. FITCON
	Estimated mean yield (tonne/ha) as difference from mean of RVP							
STOR	-0.84	-0.82	-0.84	-1.01	-1.26	-1.26	-1.26	-1.26
IPO	-0.01	0.00	-0.01	0.01	-0.16	-0.16	-0.15	-0.15
ILO	-0.37	-0.37	-0.37	-0.47	-0.53	-0.53	-0.53	-0.60
JLTIMO	-0.33	-0.34	-0.33	-0.32	0.05	0.05	0.05	0.00
ITANIA	-1.23	-1.23	-1.23	-1.05	-0.84	-0.84	-0.84	-0.77
OLMAN	-1.26	-1.27	-1.26	-1.20	-0.87	-0.88	-0.87	-0.90
ETILA					-1.11	-1.11	-1.11	-1.12
LMET					-2.04	-2.07	-2.00	-1.57
ORET					-1.16	-1.16	-1.16	-1.37

able 5.5: Ranking of adjusted means from efficient analysis

	RANKING OF ADJUSTED VARIETY MEANS						
ANALYSIS WITH	RVP	ASTOR	LIPO	WILO	MULTIMO	TITANIA	TOLMAN
7 VARIETIES	1	5	2	4	3	6	7
0 VARIETIES	2	7	3	4	1	5	6

able 5.6: Residuals from two-stage fitting constants analysis (with variety means and year effects removed) - IRG C management first harvest year total season DM yield (tonne/hectare)

	HARVEST YEAR				
VARIETY	1975	1976	1977	1978	1979
RVP	-0.6	-0.6	0.3	0.1	0.6
ASTOR	-0.0	0.0			
LIPO		-0.2	0.2		
WILO		0.1	-0.1		
MULTIMO				-0.0	0.0
TITANIA				0.3	-0.3
TOLMAN				-0.1	0.1
TETILA	-0.0	0.3	0.2	0.1	-0.5
ELMET	0.6		-0.6		
ADRET		0.4		-0.4	

years in which RVP performs less well will have their over-years mean yield adjusted upwards, while other varieties will have their mean yields reduced. The introduction of more varieties into the analysis gives a sounder base for measuring the environment. As a consequence, the adjusted variety means will be more accurate.

It will be clear that care is needed in the selection of additional varieties for inclusion in analyses. For example, the variety ELMET performed much less well in 1977 when yields were high than in 1975 when yields were generally low. In this respect the variety would appear to be atypical. Thus, there is little to be gained by including it as a representative of other varieties in an analysis.

The performance of ELMET illustrates a further point. The large adjustments shown by the augmented fitting constants estimates reflect between-year sensitivity differences which are not supported by within-year evidence. The sensitivity coefficient estimate, on which the adjusted mean for ELMET is based, is 0.56 (± .178). The within-year sensitivity coefficients are 0.98 (± .120) and 0.85 (± .086). Therefore, to use estimates of sensitivity which take no account of seasonal differences could lead to misinterpretations. ELMET may be less sensitive than other varieties. On the other hand ELMET may have changed as a variety over time.

5.3.5 The efficiency of fitting constants in herbage variety trials

As a least squares procedure, fitting constants provides unbiased mean estimates which also have minimum variance.

Fitting constants estimates are unbiased and valid even in the presence of variety x environment interactions provided the environments experienced by each variety are a random sample (Patterson, 1978). This condition for validity is not unique to fitting constants; it is implicit in other methods (Finney, 1980).

The variance that is minimised in the fitting constants analysis will inevitably be heterogeneous: the distinctive contribution of years and centres to total variance is apparent from section 3.4; differences in the variability of individual varieties have also been seen (section 4.3). Failure to take account of these differences in variances must lead to some inefficiencies in estimation.

It may be seen from the example in section 5.3.4, that the effectiveness of fitting constants can depend to a substantial degree on an adequate number of varieties being brought into the analysis to provide a reasonable estimate of each of the environmental effects. Unless this is done much of the benefits of fitting constants may be lost. Where the main link between environments lies only through one variety then the relative efficiency of fitting constants must approach that of generally inferior methods.

5.3.6 Selection and estimation

The use of the same trials data to select the best varieties, and also to estimate their future performance, will produce biased estimates of means (Finney, 1964). This happens because those varieties which yield better in trials than their true yields are the ones which are more likely to be selected. Means based on these results tend to overestimate how new varieties will perform in practice.

Finney (1964) has shown how to estimate the size of the average bias. However, there are practical difficulties in using the estimates to correct for bias in individual variety comparisons (Patterson and Silvey, 1980).

The effects of bias will be longer-lasting in herbage than with other species, since herbage varieties do not remain in trials after recommendation to provide the additional data which would eventually nullify the bias. Nevertheless, because only one recommended variety (the control) is grown in trials with candidate varieties, the bias will be concentrated in estimates of differences between the control and other recommended varieties. Estimates of differences amongst other recommended varieties should not be influenced by bias. Thus, the yield of the control variety relative to that of other varieties is likely to be underestimated in herbage variety testing.

5.4 THE USE OF TRANSFORMATIONS

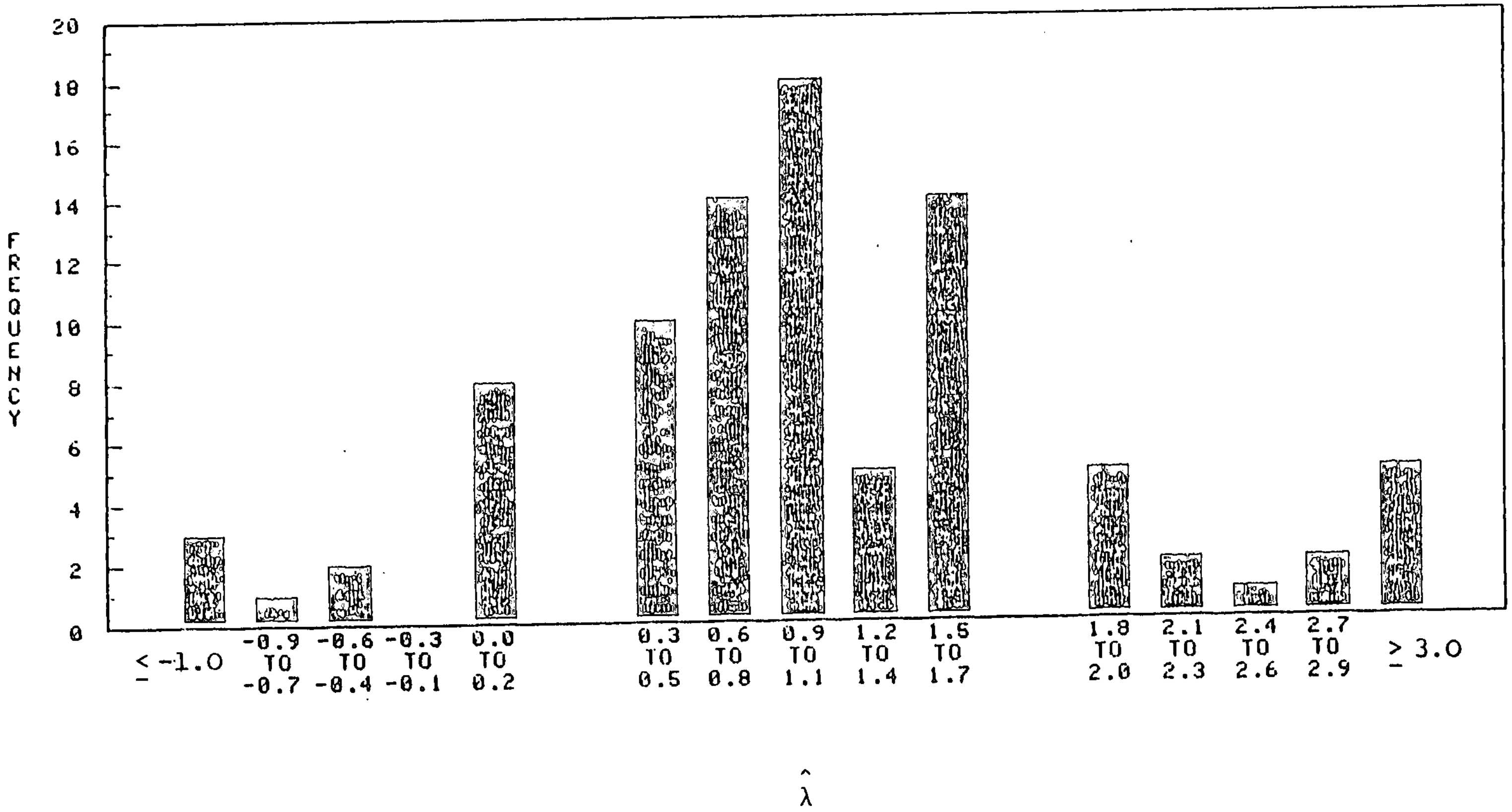
There are several important examples in the literature of the application of transformations to agricultural crop work. Fisher and Mackenzie (1923) showed that the effects of variety and manuring treatments on yields of potatoes could be represented by a product formula. Balmukand (1928) proposed that the joint effects of fertiliser became additive after a reciprocal transformation had been applied to yield data, while the original scale gave normality and constant variance. Finlay and Wilkinson (1963) used a logarithmic transformation to give constant variance in the analysis of barley grain yield data.

There are some indications from the herbage variety data of both heterogeneity of variances (amongst maturity and ploidy groups) and of non-additivity (associated with sensitivity differences). Since there is no strong evidence to guide in the choice of transformation, we consider here the general power family of transformations, described by Box and Cox (1964).

Maximum likelihood estimates of the power parameter λ were derived from an analysis fitting main effects to a variety x trials table of mean yields which were transformed to power λ. Independent estimates of λ were obtained from an analysis of 90 variety x trial-within-year data sets, from five species, two managements, five sowing years, and two harvest years. A frequency distribution of the estimates of λ is shown in Figure 5.1.

The wide spread in the distribution of λ values shows that the analysis of some data sets will be improved by values of λ

Figure 5.1: Frequency distribution of $\hat{\lambda}$ when variety and centre effects are fitted to 90 herbage variety data sets.



as low as -1 (the reciprocal transformation), and some by values as high as 3. However, the mode of the distribution is positioned close to $\lambda = 1$ (no transformation). None of the species give consistently high or low values of λ. As a general rule, the larger the data set then the closer is λ to 1.

In the routine estimation of variety performance the analysis procedures must be established in advance of data collection since it is important for all concerned with the future of varieties to know the basis on which decisions are to be made. As a consequence, the choice of scale should not be changed to suit a particular data set. Necessarily the choice must be based on long-term average experience. The results in Figure 5.1 indicate that, for total season herbage yields, analysis on an untransfomed scale will be reasonable in most cases although far from optimal in a few cases.

Mean trial yields from the five species ranged from 6 to 18 tonne/hectare. No very low yields were recorded. A separate examination was made of white clover yield data from five years of NL trials. In these trials mean clover yields ranged from 0.4 to 7.9 tonne/hectare. The estimated values of λ, derived from an analysis of each years data separately, were 0.8, 0.7, 1.0, 0.4, and 0.6. The distribution of the values suggests an optimum λ of somewhat less than one. However, the evidence is equivocal and points to the need for further investigation in this area.

A feature noted in the present investigation has been how an analysis based on small data sets can occasionally suggest the need for strong transformations. On closer study the evidence for the transformations was often found to be based on very few values. Recently, Atkinson (1982) pointed out the circular nature of this situation: transformations bring apparent outliers into agreement with the data; but the evidence for the transformations rests with the outliers. In his paper, Atkinson described plotting techniques for assessing the influence of individual observations on the estimated transformation parameters.

CHAPTER 6

DESIGN OF A TRIALS SYSTEM

6.1 INTRODUCTION

For plant breeders, official variety testing represents the final stages in a long period of development. For growers, official testing is the first step in finding out how useful a breeder's material may be in improving production. For society at large, official testing is one method for ensuring that good varieties are put into agricultural use as efficiently as possible. The efficiency with which this transfer takes place depends critically, where there are well-educated farmers and good communications, on the effectiveness of the trials system.

The design of a trials system has several aspects. These include: measurement techniques; the selection of treatments; the choice and number of, experimental units; the allocation of treatments to experimental units; the rules for estimating parameters from experimental data, and for decision making.

Many of these aspects have already been touched on in earlier chapters. We concentrate here on the number, and distribution of, the experimental units. Possible criteria for judging the effectiveness of alternative trial arrangements are reviewed. The herbage variety testing system is assessed against some of these criteria.

6.2 CRITERIA

Three statistical criteria for assessing a trials system are considered. These are, critical difference, acceptance probability and potential gain.

A critical difference is the difference between one variety and another which, if the true difference is zero, will be exceeded in only a small proportion of cases. In practice, the difference to be assessed is that between a candidate variety and a standard (see Chapter 5.2).

An acceptance probability is the probability that a variety of known performance relative to the standard will be accepted. Thus, the probability is influenced by the accuracy of the trials system as well as, for any individual variety, the size of the difference between its true performance and the acceptance standard.

Potential gain measures the average difference in performance between all varieties entering trials and those finally recommended. Gain is a function of the proportion of varieties accepted as well as the efficiency of the trials system. For a fixed proportion of varieties accepted, the larger is the gain then the more efficient is the trials system.

The three criteria are closely related. Critical differences measure the precision of the trials but take no account of the decision procedures for promoting varieties. Acceptance probabilities incorporate a decision rule that leads to acceptance of all varieties above a standard. Potential gain uses a decision rule that accepts a fixed proportion of the best varieties.

It must be stressed that the three criteria are measures of precision only. They take no account of possible bias which may affect the applicability of trial results (Section 6.4). Neither do they allow for estimation bias (Section 5.3). Also the relative costs and benefits of trials systems are not part of the criteria, though the benefits may be deduced from acceptance probabilities and percentage gains.

In the application of criteria to the choice of a trials system, gain and acceptance probabilities cannot be regarded as simple alternatives. They each describe different aspects of the same trials system. One deals with risks to the breeder. The other is concerned with gains to the country. Both aspects are important and both must be taken into account.

Potential gain does not attempt to a measure what might be achieved in commercial agriculture. It only indicates what should happen if all recommended varieties are grown to the same extent. In practice, the best varieties are more widely grown and these are more likely to be recommended whatever trials system operates.

When decisions are based on several characters, as occurs in official testing, then gain must be measured in terms of a utility function (Chapter 5.2). In herbage variety testing a utility function must give greater weight to gains in the second harvest year since such gains might indicate better long-term yield potential. Also gains in conservation management, under which yields are most fully utilised in practice, may be more important than similar gains in frequent management.

In the following section some aspects of the planning of a series of herbage variety trials are examined using critical differences and acceptance probabilities.

6.3 APPLICATION OF CRITERIA

6.3.1 Critical differences

The components of variance in Chapter 3 can be used to estimate the relative efficiency of several trial systems.

Suppose that a candidate variety is sown with a control variety at m centres in each of n years with r replicates per trial. The standard error of the estimated mean difference is $\surd(2V)$ where

$$V = \frac{\sigma^2_{VC}}{m} + \frac{\sigma^2_{VY}}{n} + \frac{\sigma^2_{VCY}}{mn} + \frac{\sigma^2_{P}}{mnr} \qquad (6.3.1)$$

and σ^2_{VC}, σ^2_{VY}, σ^2_{VCY}, and σ^2_{P} are the 'variety x centre', 'variety x year', 'variety x centre x year' and experimental error variance components. The critical difference is given by

$$D_\alpha = d_\alpha \surd(2V) , \qquad (6.3.2)$$

where d_α is a value from the normal distribution tables that is exceeded with probability α.

Critical differences are shown in Table 6.1 for varying numbers of trials. The results in the table are based on an average of the variances for first and second years total season DM yield as given in Table 3.3.

It can be seen from Table 6.1 that although variability within a trial is large, nevertheless, increasing within-trial replication has only a small effect on precision. The maximum difference between a critical difference in the first four columns (2 replicates) and a corresponding critical difference in the last four columns (3 replicates) is 0.3%.

Table 6.1: Critical percent difference in yield [i.e. % difference in yield between two varieties which, if there is no real difference will be exceeded in 2.5% of cases] based on mean of first and second harvest years variation.

TRIAL SYSTEM

REPLICATES		2				3			
YEARS		1		2		1		2	
CENTRES		7	11	7	11	7	11	7	11
SPECIES	MAN.	% critical difference							
PRG	C	11.2	10.3	8.0	7.3	11.0	10.1	7.8	7.2
	F	5.3	4.5	4.0	3.3	5.0	4.2	3.7	3.1
IRG	C	9.9	8.9	8.1	6.3	9.6	8.7	7.9	6.2
	F	7.3	6.4	5.6	4.8	7.0	6.2	5.4	4.7
TIM	C	6.5	5.5	4.8	4.0	6.2	5.3	4.6	3.9
	F	4.8	4.0	3.7	3.0	4.5	3.8	3.5	2.9
CFT	C	6.9	5.9	5.2	4.4	6.6	5.7	5.0	4.3
	F	6.1	5.5	4.6	4.0	5.9	5.3	4.4	3.9
RCL	C	13.2	11.1	10.2	8.4	13.1	10.9	10.1	8.4

The much higher precision obtained with frequent management than with conservation management, particularly in perennial ryegrass, is also apparent from Table 6.1. Also, differences in timothy and cocksfoot are more precisely determined than in other species.

Figure 6.1 emphasises the importance of maintaining a balance in the numbers of years and centres to achieve the greatest precision for a given total number of trials. However, in practice, the number of testing years is limited and further gains in precision can only come through increasing the number of centres.

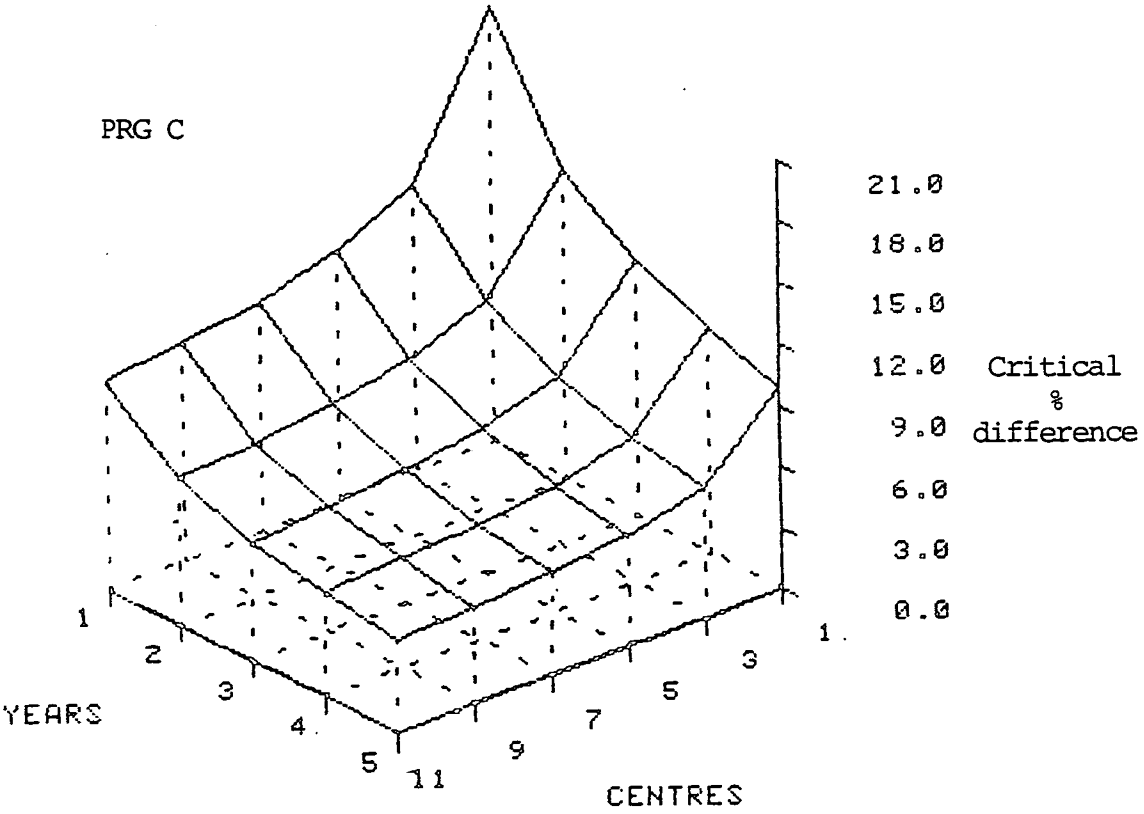
Seasonal factors impose major restraints on improving the precision of a trials system. It will be apparent from the formula (6.3.1) why this should be so. When the 'variety x year' component is non-zero and where, as occurs in most crop-testing programmes, the number of trial years is restricted, then the 'variety x year' component represents a limit below which V cannot be reduced, irrespective of the number of centres used.

6.3.2 Acceptance probabilities

Table 6.2 shows the probability of a variety being rejected, i.e. one minus the probability of acceptance, given that the variety exceeds the standard on each of four yield characters.

From the table it will be seen that as the number of trials decreases then the probability of rejection increases. A corollary is that, as the number of trials decreases, the probability of wrongly accepting varieties that do not meet the

Figure 6.1: Effect on critical difference (p = 0.025) of varying numbers of years and centres - data are PRG total season DM yield



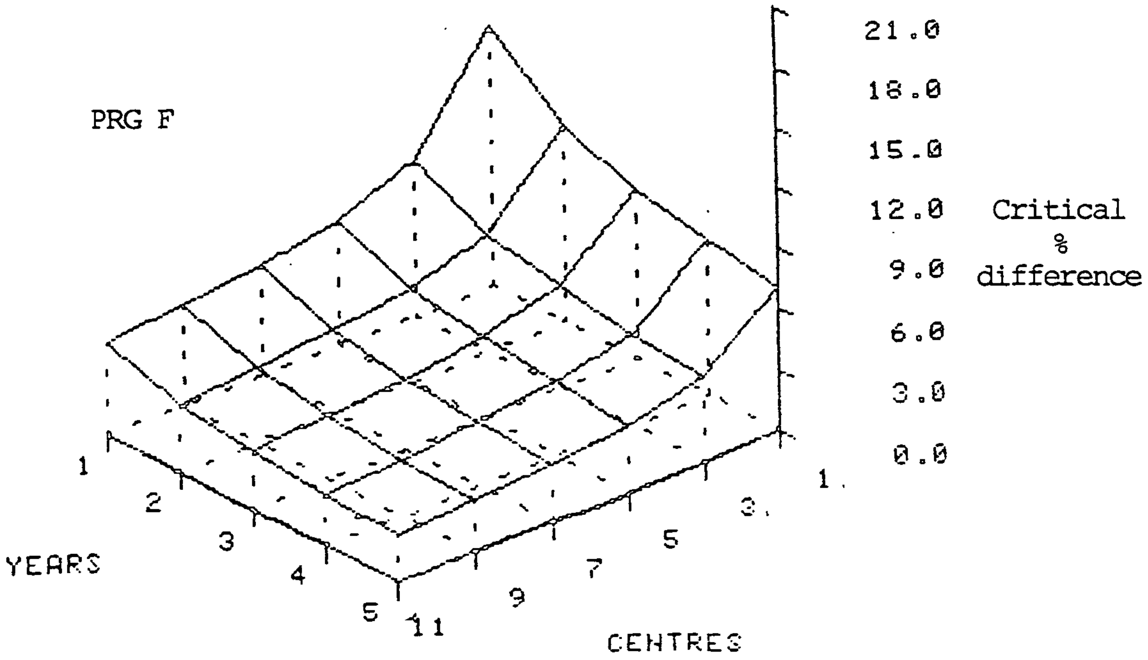


Table 6.2: Probability of rejecting a new variety under several trial systems

TRIAL SYSTEM

REPLICATES	2				3			
YEARS	1		2		1		2	
CENTRES	7	11	7	11	7	11	7	11
SPECIES	Joint probability of rejection when true yield of new variety exceeds acceptance standard by 2.5% on each of four yield measures (i)							
PRG	.65	.61	.54	.47	.63	.59	.52	.47
IRG	.67	.63	.56	.52	.65	.62	.56	.50
TIM	.51	.43	.37	.26	.48	.40	.34	.24
CFT	.55	.49	.42	.35	.53	.48	.40	.33
RCL	.54	.51	.48	.44	.54	.50	.48	.44
	Joint probability of rejection when true yield of new variety exceeds acceptance standard by 5% on each of four yield measures (i)							
PRG	.37	.32	.21	.18	.35	.30	.20	.17
IRG	.39	.32	.22	.16	.37	.31	.20	.15
TIM	.15	.08	.05	.02	.13	.07	.04	.01
CFT	.21	.14	.08	.04	.19	.13	.07	.03
RCL	.38	.32	.29	.22	.37	.31	.28	.22

Note: (i) The four measures for PRG, IRG, TIM and CFT are first and second harvest years total season DM yield in each of C and F management; there are only two measures for RCL - first and second harvest years total season DM yield in C management.

standards will also increase.

The results in Table 6.2 indicate that in a trials system with two replicates sown in two years at each of eleven centres, approximately a half of the perennial ryegrass varieties whose true yields exceed the standard by 2.5% will in fact be rejected. Approximately one in six of perennial ryegrass varieties with yields 5% more than the standard will be rejected.

The significance of these results depends on the level at which the standards are set. However Table 6.2 can be used to determine the level at which the standards might be set for a given number of trials.

6.3.3 Modifying an existing trials system

If changes are required in an existing herbage variety testing programme then a number of options are available. Where the number of centres is reasonably large, a small change in their number will have limited effect on the precision of the trials system while changing the total cost broadly in proportion to the number of centres involved. A change in the testing period will result in a significant change in precision; total testing costs are unlikely to be changed substantially since it is the size of each trial rather than the number of trials that will be affected. A change in the number of replicates is unlikely to affect precision greatly unless it is reduced below two. Then internal checks on individual trial performance will be lost, which would not be satisfactory.

6.3.4 Monitoring a trials system

The present investigation is based on data from a limited number of seasons. Nevertheless the results do provide a preliminary check on the performance of the official herbage variety testing system. The results also make possible the establishment of objective acceptance standards. In time, systematic monitoring of the testing process will give additional information on which to adjust these standards as necessary.

The components of variance from which the criteria in this chapter have been derived are averages and, as we have seen, some varieties can vary more than others in peformance. However, we are concerned with planning for the future and for this reason it does not seem unreasonable to base plans on average variances. At the same time, the checking procedures of section 4.3 are available to identify varieties with exceptional variability. In this context, the official variety testing system can be likened to a manufacturing quality control scheme where average variability in the system is used as a basis for setting up acceptance limits, and where both average performance of individual batches and variability in performance are monitored.

6.4 LIMITATIONS OF TRIALS

Trials are used to predict what may happen in a future season. If a future season is abnormal then average performance in past trials may not represent a good prediction. Nevertheless, in the absence of information about the season, an average provides a reasonable basis for decision.

The accuracy with which trials estimate future commercial performance does not depend solely on variation that can be measured within the trials system. It is also affected by how closely testing operations and conditions reflect commercial practice. The selection and source of seed will be important. Any of these factors may favour some varieties more than others and thus may introduce a bias of unknown amount into estimates of relative variety performance. However, testing in any area involves making maximum use of scarce resources. Rarely can one afford to simulate normal practice. The extent to which total variation - imprecision and bias - is minimised in official herbage variety trials may be assessed by the degree to which its results are accepted by the user.

CONCLUSIONS

[Figures in parenthesis refer to sections where the conclusions are developed.]

(2.2) By the use of lattice designs in herbage variety trials with large numbers of varieties, a reduction in within-trial variation may be achieved that will approximate to an increase from two or three replicates in a complete block arrangement.

(2.3) In the joint analysis of individual-harvest and total-over-harvests data from a lattice-designed experiment, a multivariate approach which takes full account of all variances and covariances within and between blocks, is the only completely efficient way of estimating treatment means. However, if the correlations between yields from different harvests are low, e.g. < 0.50, and the correlations are approximately the same in blocks as they are amongst plots, and if the ratio of the block to plot variances does not vary greatly between harvests, then the loss of efficiency from using a univariate lattice analysis procedure is not likely to be large. These conditions appear to be fulfilled in DM yield from official herbage variety trials. Thus, a univariate analysis procedure can be recommended with some assurance that differences between the sum of adjusted means for individual harvests will not differ substantially from adjusted means for totals over harvests.

(3.4) Variation in variety performance from trial to trial increases as the general level of yield increases. This pattern appears to be associated with meteorological factors.

(4.3) Differences are noted in the variability of individual varieties. The variability of perennial ryegrass varieties under conservation management is influenced by time of maturity, ploidy, and to some extent by country of origin. A special kind of variability is identified amongst tetraploid varieties which tend to perform relatively better when mean trial yields are high.

(4.4) Dissimilarities between centres in the way varieties perform suggest that it may be possible to associate some of these differences with specific environmental factors.

(5.3) The efficiency with which future performance of varieties can be estimated may be improved by including more varieties in over-trials analysis. Care is needed in the choice of these additional varieties.

(5.3) In official UK herbage variety trials the yield of control varieties is underestimated relative to that of other varieties as a result of selection bias.

(5.4) The efficiency of procedures for estimating future variety performance will not be improved substantially by analysis on a transformed scale.

(6.3) For a given total number of trials, maximum precision in estimates of future variety performance is achieved when the numbers of centres and years are broadly the same. Differences between varieties are much more accurately assessed under frequent management than under conservation management, and for timothy and cocksfoot than for perennial ryegrass, Italian ryegrass and red clover.

REFERENCES

ATKINSON, A.C. (1969). The use of residuals as a concomitant variable. Biometrika, 56, 33-41.

ATKINSON, A.C. (1982). Regression diagnostics, transformations and constructed variables. J.R. Statist. Soc. B, 44, in press.

BALMUKAND, B. (1928). Studies in crop variation. V. The relation between yield and soil nutrients. J. Agric. Sci., 18, 602-627.

BARTLETT, M.S. (1938). The approximate recovery of information from field experiments with large blocks. J. Agric. Sci., 28, 418-427.

BARTLETT, M.S. (1978). Nearest neighbour models in the analysis of field experiments. J.R. Statist. Soc. B, 40, 147-174.

BOSE, R.C. and NAIR, K.R. (1962). Resolvable incomplete block designs with two replications. Sankhya, A24, 9-24.

BOX, G.E.P. and COX, D.R. (1964). An analysis of transformations. J.R. Statist. Soc. B, 26, 211-252.

COCHRAN, W.G. (1939). Long-term agricultural experiments. J.R. Statist. Soc. Suppl., 6, 104-140.

COCHRAN, W.G. (1940). A survey of experimental design. USDA (Mimeo).

COCHRAN, W.G. and COX, G.M. (1957). Experimental designs. New York: Wiley.

COLE, J.W.L. and GRIZZLE, J.E. (1966). Applications of multivariate analysis of variance to repeated measurements experiments. Biometrics, 22, 810-828.

CURNOW, R.N. (1961). Optimal programmes for varietal selection. *J.R. Statist. Soc.* B, 23, 282-318.

DANFORD, M.B., HUGHES, H.M. and McNEE, R.C. (1960). On the analysis of repeated measurements experiments. *Biometrics*, 16, 547-565.

DAVID, H.A. (1967). Resolvable cyclic designs. *Sankhya*, A29, 191-8.

DIGBY, P.G.N. (1979). Modified joint regression analysis for incomplete variety x environment data. *J. Agric. Sci.*, 93, 81-86.

EBERHART, S.A. and RUSSEL, W.A. (1966). Stability parameters for comparing varieties. *Crop. Sci.*, 6, 36-40.

EVANS, J.C. and ROBERTS, E.A. (1979). Analysis of sequential observations with applications to experiments on grazing animals and perennial plants. *Biometrics*, 35, 687-693.

FINLAY, K.W. and WILKINSON, G.N. (1963). The analysis of adaptation in a plant breeding programme. *Aust. J. Agric. Res.*, 14, 742-754.

FINNEY, D.J. (1956). Multivariate analysis and agricultural experiments. *Biometrics*, 12, 67-71.

FINNEY, D.J. (1958). Statistical problems in plant selection. *Bull. Inst. Int. Stat.*, 36, 242-268.

FINNEY, D.J. (1964). The replication of variety trials. *Biometrics*, 20, 1-15.

FINNEY, D.J. (1980). The estimation of parameters by least squares from unbalanced experiments. *J. Agric. Sci.*, 95, 181-189.

FISHER, R.A. and Mackenzie, W.A. (1923). Studies in crop variation. II. The manurial response of different potato varieties. J. Agric. Sci., 13, 311-320.

FISHER, R.A. (1925). Statistical methods for research workers. Edinburgh: Oliver and Boyd.

FREEMAN, G.H. (1973). Statistical methods for the analysis of genotype-environment interactions. Heredity, 31, 339-354.

FREEMAN, G.H. and DOWKER, B.D. (1973). The analysis of variation between and within genotypes and environments. Heredity, 30, 97-109.

FREEMAN, G.H. (1975). Analysis of interactions in incomplete two-way tables. Applied Statistics, 24, 46-55.

FREEMAN, G.H. and CRISP, P. (1979). The use of related variables in explaining genotype-environment interactions. Heredity, 42, 1-11.

GOWER, J.C. (1966). Some distance properties of latent root and vector methods used in multivariate analysis. Biometrika, 53, 325-338.

HANSON, W.D. (1964). Genotype-environment interaction concepts for field experimentation. Biometrics, 20, 540-552.

HARDWICK, R.C. and WOOD, J.T. (1972). Regression methods for studying genotype-environment interactions. Heredity, 28, 209-222.

HARSHBARGER, B. (1949). Triple rectangular lattices. Biometrics, 5, 1-13.

HARTLEY, H.O. and RAO, J.N.K. (1967). Maximum likelihood estimation for the mixed analysis of variance model. Biometrika, 54, 93-108.

HARVILLE, D.A. (1977). Maximum likelihood approaches to variance component estimation and to related problems. *Jour. Amer. Stat. Assoc.*, 72, 320-340.

HENDERSON, C.R. (1953). Estimation of variance and covariance components. *Biometrics*, 9, 226-252.

HILL, J. (1976). Genotype-environment interactions - a challenge for plant breeding. *J. agric. Sci.*, 85, 477-494.

JARRETT, R.G. and HALL, W.B. (1978). Generalized cyclic incomplete block designs. *Biometrika*, 65, 397-401.

JOHN, J.A. (1966). Cyclic incomplete block designs. *J.R. Statist. Soc.* B, 28, 345-360.

JOHN, J.A., WOLOCK, F.W. and DAVID, H.A. (1972). Cyclic designs. *Nat. Bur. Standards Appl. Math. Ser.*, 62.

KALTSIKES, P.J. (1970). Genotype-environment interaction variances in yield trials of fall rye. *Canadian Journal of Plant Science*, 50, 77-80.

KEMPTON, R.A. and HOWES, C.W. (1981). The use of neighbouring plot values in the analysis of variety trials. *Applied Statistics*, 30, 59-70.

PAPADAKIS, J.S. (1937). Methode statistique pour des experiences sur champ. *Bull. Inst. Amel. Plantes a Salonique*, no. 23.

PATTERSON, H.D. (1953). The analysis of the results of a rotation experiment on the use of straw and fertilizers. *J. Agric. Sci.*, 43, 77-88.

PATTERSON, H.D. (1978). Routine least squares estimation of variety means in incomplete tables. *J. Natn. Inst. Agric. Bot.*, 14, 401-413.

PATTERSON, H.D. and SILVEY, V. (1980). Statutory and recommended list trials of crop varieties in the United Kingdom. J.R. Statist. Soc. A, 143, 219-253.

PATTERSON, H.D., SILVEY, V., TALBOT, M. and WEATHERUP, S.T.C. (1977). Variability of yields of cereal varieties in UK trials. J. Agric. Sci., 89, 239-245.

PATTERSON, H.D. and THOMPSON, R. (1971). Recovery of inter-block information when block sizes are unequal. Biometrika, 58, 545-554.

PATTERSON, H.D. and THOMPSON, R. (1974). Maximum likelihood estimation of components of variance. Proc. of the 8th Int. Biom. Conf., 197-207.

PATTERSON, H.D. and WILLIAMS, E.R. (1976). A new class of resolvable block designs. Biometrika, 63, 83-92.

PATTERSON, H.D., WILLIAMS, E.R. and HUNTER, E.A. (1978). Block designs for variety trials. J. Agric. Sci., 90, 395-400.

PEARCE, S.C. (1953). Field Experimentation with Fruit Trees and Other Perennial Plants. Commonwealth Bureau of Horticulture and Plantation Crops, Kent.

PEARCE, S.C. (1978). The control of environmental variation in some West Indian maize experiments. Trop. Agric., 55, 97-106.

PEARCE, S.C. (1980). Randomised blocks and some alternatives: a study in tropical conditions. Trop. Agric., 57, 1-10.

PEARCE, S.C. and MOORE, C.S. (1976). Reduction of experimental error in perennial crops, using adjustment by neighbouring plots. Exp. Agric., 12, 267-272.

PEARL, R. and SURFACE, F.M. (1916). A method of correcting for soil heterogeneity in variety tests. J. Agric. Res., 5, 1039-1050.

RASMUSSON, D.C. and LAMBERT, J.W. (1961). Variety x environment interactions in barley variety tests. Crop Sci., 1, 261-2.

ROWELL, J.G. and WALTERS, D.E. (1976). Analysing data with repeated observations on each experimental unit. J. Agric. Sci., 87, 423-432.

SHUKLA, G.K. (1972a). Some statistical aspects of partitioning genotype-environmental components of variability. Heredity, 29, 237-245.

SHUKLA, G.K. (1972b). Application of some multivariate techniques in the analysis and interpretation of the genotype-environment interaction. Paper presented at the symposium on genotype x environment interactions, Birmingham University, 1972.

SILVEY, V. (1967). Statistical aspects of the design and analysis of N.I.A.B. cereal trials. J. Natn. Inst. Agric. Bot., 11, 91-103.

SNEDECOR, G.W. and HABER, E.S. (1946). Statistical methods for an incomplete experiment on a perennial crop. Biometrics, 2, 61-67.

SPRAGUE, G.F. and FEDERER, W.T. (1951). A comparison of variance components in corn yield trials. 2. Error, year x variety, location x variety, and variety components. Agron. J., 43, 535-541.

STEEL, R.G.D. (1955). An analysis of perennial crop data. Biometrics, 11, 201-212.

TALBOT, M. and ROBINSON, D.L. (1980). CVT - a statistical computing and data management system in agricultural crop research. Compstat 1980, Proceedings in Computational Statistics, 81-87. Vienna: Physica-Verlag.

WILLIAMS, E.R. (1977). Iterative analysis of generalized lattice designs. Austral. J. Statist., 19, 39-42.

WISHART, J. (1938). Growth-rate determinations in nutrition studies with the bacon pig, and their analysis. Biometrika, 30, 16-28.

YATES, F. (1933). The principles of orthogonality and confounding in replicated experiments. J. Agric. Sci., 23, 108-145.

YATES, F. (1936). A new method of arranging variety trials involving a large number of varieties. J. Agric. Sci., 26, 424-455.

YATES, F. (1939). The recovery of inter-block information in variety trials arranged in three-dimensional lattices. Ann. Eugen., 9, 136-156.

YATES, F. (1940). The recovery of inter-block information in balanced incomplete block designs. Ann. Eugen., 10, 317-325.

YATES, F. (1970). Experimental Design. London: Griffin.

YATES, F. and COCHRAN, W.G. (1938). The analysis of groups of experiments. J. Agric. Sci., 28, 556-580.

YOUNG, J.C. (1972). The moments of a distribution after selection with error. J. Amer. Statist. Assoc., 67, 206-210.