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Experimental Designs for Off-station Agronomy Trials

by

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This paper was written by Roger G. Petersen, a statistician and biometrician working at ICARDA on sabbatical leave from Oregon State University, USA.

The paper was written primarily for ICARDA scientists, but will also be of use to researchers conducting off-station agronomic trials at other institutions.

CONTENTS

EXPERIMENTAL DESIGNS FOR OFF-STATION AGRONOMY TRIALS

Introduction:

The aim of off-station agronomy trials is to determine, under a wide variety of conditions, which of the factors of production have a significant effect on yield and how the factors interact with each other as they affect yield. In designing these trials a number of considerations come into play. They should be conducted at several locations so that the effects may be examined under a wide variety of conditions. They should be relatively small because of the limited resources of any research program, yet they should provide reasonable precision for estimating the effects of interest. For practical reasons they should allow the use of large plots for some treatments and small plots for others. They should permit relatively uncomplicated statistical analysis of the results.

The experimental designs presented here are an attempt to meet these restrictions. Each design requires only thirty two plots. They permit the simultaneous examination of five or six factors of production. They provide at least nine degrees of freedom for estimating error. Some of the plans allow the trial to be split in one or more ways for convenience in applying treatments.

In all of these designs each factor is tested at only two levels, or rates, a high level and a low level. Usually, but not necessarily, the low level would be the absence of the factor. In some cases it might be known that a minimum amount of the factor, such as nitrogen, must be added to produce any yield at all. In this case the low level would consist of a minimum application of the factor . In some instances a factor might have qualitative rather than quantitative levels. For example, drilling and broadcasting might represent a "method of seeding" factor. In this case one method, drilling, would arbitrarily be called the high level while the other method, broadcasting, would be called the low.

Depending on the choice of design, most of the main effects and most of the two factor (first order) interactions can be estimated. It is assumed that interactions which involve three or more factors are negligible. The sums of squares for these interactions are combined as an estimate of error. For this reason replication is not necessary for these designs. Note, however, that every factor occurs at the high level in 16 of the plots and at the low level in the other 16 plots. Hence, the designs have a degree of "hidden" replication.

Using the Designs:

Select a design according to the number of factors to be used and according to whether the experiment must be split to apply one or more of the factors. Designate each factor with a letter of the alphabet, beginning with a . Each design consists of 32 plots, represented by rectangles on the plan. The letters in the rectangle designate the treatment combination to be applied to that plot. Presence of the letter indicates that the factor is applied at the high level, while absence indicates that the factor is applied at the low level. The symbol (1) indicates that all factors are at the low level.

Care must be taken to apply the factors in exactly the combinations shown in the plan. Otherwise the analysis of the data will produce erroneous results. The treatments have already been assigned to the plots at random, so no further randomization is necessary.

A work sheet for the statistical analysis of the results is included with each plan. Instructions for the use of this work sheet, and a numerical example are given following the plans.

Plan 5.0 Five Factors

All main effects and two factor interactions estimable.

bcd	ab	abce	abcde
cd	ac	abde	bcde
bd	abd	de	bc
ce	abc	e	acd
bce	b	ad	be
c	d	(1)	ade
ae	cde	a	bde
ace	abe	abcd	acde

Degrees of Freedom for Error = 16

Example:

Factor		Letter Absent	Letter Present
a	Nitrogen	none	50 kg/ha
b	Potassium	none	20 kg/ha
c	Phosphorus	none	50 kg/ha
d	Minor elements	none	2 kg/ha
e	Weed control	none	Herbicide

Five Factors

Analysis work sheet

Treat.	Yield	I	II	III	IV	V	Effect	SS
(1) a							Total A	
b ab							B AB	
c ac							C AC	
bc abc							BC **	
d ad							D AD	
bd abd							BD **	
cd acd							CD **	
bcd abcd							** **	
e ae							E AE	
be abe							BE **	
ce ace							CE **	
bce abce							** **	
de ade							DE **	
bde abde							** **	
cde acde							** **	
bcde abcde							** **	

** Combine for error (16 d.f.)

SS = $(V)^2/32$

SSE = $\sum(SS^{**})$

Minimum SS_α for significance

1%, $SS_{.01}$ = (8.53)(MSE)

5%, $SS_{.05}$ = (4.49)(MSE)

10%, $SS_{.10}$ = (3.05)(MSE)

MSE = SSE/16

$\bar{\bar{y}}$ = Total/32

e_k = $E_k/32$, where E_k = Entry in V for effect K.

<u>Plan 5.1</u> <u>Five Factors</u> - <u>one split</u>

All main effects except E estimable.

All two factor interactions estimable.

(1)		e	
(1)	cd	de	e
ab	d	be	abce
bc	bcd	bce	abcde
abd	acd	ace	cde
abc	a	bde	bcde
c	bd	acde	abe
abcd	b	ce	ae
ad	ac	ade	abde

Degrees of freedom for error = 16

Example:

Factor		Absent	Letter	Present
a	Nitrogen	none		50 kg/ha
b	Potassium	none		20 kg/ha
c	Phosphorus	none		50 kg/ha
d	Weed control	none		Herbicide
e	Irrigation	none		Once

Five Factors - One Split

Analysis Work Sheet

Treat.	Yield	I	II	III	IV	V	Effect	SS
(1) a							Total A	——
b ab							B AB	
c ac							C AC	
bc abc							BC **	
d ad							D AD	
bd abd							BD **	
cd acd							CD **	
bcd abcd							** **	
e ae							Block AE	——
be abe							BE **	
ce ace							CE **	
bce abce							** **	
de ade							DE **	
bde abde							** **	
cde acde							** **	
bcde abcde							** **	

** Combine for error (16 d.f.)

SS = $(V)^2/32$

$SSE = \Sigma(SS^{**})$

MSE = SSE/16

$\bar{\bar{y}}$ = Total /32

$e_k = E_k/32$, where E_k = Entry in V for effect K.

Minimum SS_α for significance

1%, $SS_{.01}$ = (8.53)(MSE)

5%, $SS_{.05}$ = (4.49)(MSE)

10%, $SS_{.10}$ = (3.05)(MSE)

Plan 5.2 Five Factors - two splits

All main effects except D and E estimable

All two factor interactions except DE estimable.

(1)	cd	ace	bde
abc	d	e	bcde
a	abd	abe	abcde
bc	bcd	ae	de
ab	abcd	be	acde
ac	acd	ce	ade
c	bd	abce	cde
b	ad	bce	abde
(1)	d	e	de

Degrees of Freedom for Error = 16

Example

Factor		Letter Absent	Present
a	Nitrogen	none	50 kg/ha
b	Potassium	none	20 kg/ha
c	Phosphorus	none	50 kg/ha
d	Planting date	Early	Late
d	Irrigation	none	Once

Five factors - Two splits

Analysis Work Sheet

Treat.	Yield	I	II	III	IV	V	Effect	SS
(1)							Total	——
a							A	
b							B	
ab							AB	
c							C	
ac							AC	
bc							BC	
abc							**	
d							Block	——
ad							AD	
bd							BD	
abd							**	
cd							CD	
acd							**	
bcd							**	
abcd							**	
e							Block	——
ae							AE	
be							BE	
abe							**	
ce							CE	
ace							**	
bce							**	
abce							**	
de							Block	——
ade							**	
bde							**	
abde							**	
cde							**	
acde							**	
bcde							**	
abcde							**	

** Combine for error (16 d.f.)

$SS = (V)^2/32$

Minimum SS_α for significance

1%, $SS_{.01} = (8.53)(MSE)$

5%, $SS_{.05} = (4.49)(MSE)$

10%, $SS_{.10} = (3.05)(MSE)$

$SSE = \sum (SS^{**})$

$MSE = SSE/16$

$\bar{\bar{y}} = \text{Total}/32$

$e_k = E_k/32$, where E_k = entry in V for effect K

Plan 5.3 Five factors - Three splits

All main effects except C, D, and E estimable

All two factor interactions except CD, CE, and DE estimable

(1)	ab	d	ae	abde
(1)	(1)	abd	e	bde
(1)	a	ad	be	de
(1)	b	bd	abe	ade
c	bc	abcd	ce	acde
c	ac	cd	abce	cde
c	c	acd	bce	abcde
c	abc	bcd	ace	bcde
	(1)	d	e	de

Degrees of Freedom for Error = 15

Example:

Factor		Absent	Letter	Present
a	Variety	Standard		Improved
b	Nitrogen	None		50 kg/ha
c	Planting Method	Broadcast		Drilled
d	Planting Date	Early		Late
e	Irrigation	None		Once

Five factors - Three splits

Analysis Work Sheet

Treat.	Yield	I	II	III	IV	V	Effect	SS
(1)							Total	—
a							A	
b							B	
ab							AB	
c							Block	—
ac							AC	
bc							BC	
abc							**	
d							Block	—
ad							AD	
bd							BD	
abd							**	
cd							Block	—
acd							**	
bcd							**	
abcd							**	
e							Block	—
ae							AE	
be							BE	
abe							**	
ce							Block	—
ace							**	
bce							**	
abce							**	
de							Block	—
ade							**	
bde							**	
abde							**	
cde							Block	—
acde							**	
bcde							**	
abcde							**	

**		Combine for error (15 d.f.)
SS	=	$(V)^2/32$
SSE	=	$\sum(SS^{**})$
MSE	=	SSE/15
$\bar{\bar{y}}$	=	Total/32
e_k	=	$E_k/32$, where E_k = entry in V for effect K.

Minimum SS_α for significance

1%, $SS_{.01} = (8.68)(MSE)$

5%, $SS_{.05} = (4.54)(MSE)$

10%, $SS_{.10} = (3.07)(MSE)$

Plan 6.0 Six factors

All main effects estimable

All two-factor interactions estimable

bcde	abef	ef	bd
bdef	ce	bf	ae
abcdef	ad	bc	de
bcdf	acef	abcd	af
abdf	(1)	be	cf
abde	acdf	abce	ac
df	cd	ab	acde
bcef	abcf	cdef	adef

Degrees of Freedom for Error = 10

Example :

Factor		Absent	Letter	Present
a	Variety	Standard		Improved
b	Nitrogen	None		50 kg/ha
c	Potassium	None		20 kg/ha
d	Phosphorus	None		50 kg/ha
e	Minor elements	None		2 kg/ha
f	Weed control	None		Herbicide

Six Factors

Analysis Work Sheet

Treat	Yield	I	II	III	IV	X	Effect	SS
(1)							Total	
af							A	
bf							B	
ab							AB	
cf							C	
ac							AC	
bc							BC	
abcf							**	
df							D	
ad							AD	
bd							BD	
abdf							**	
cd							CD	
acdf							**	
bcdf							**	
abcd							EF	
ef							E	
ae							AE	
be							BE	
abef							**	
ce							CE	
acef							**	
bcef							**	
abce							DF	
de							DE	
adef							**	
bdef							**	
abde							CF	
cdef							**	
acde							BF	
bcde							AF	
abcdef							F	

**		Combine for error
SS	=	$(V)^2/32$
SSE	=	$\sum(SS^{**})$
MSE	=	SSE/10
$\bar{\bar{y}}$	=	Total /32
e_k	=	$E_k/32$, where E_k = Entry in V for effect K

Minimum SS_α for significance

1%, $SS_{.01}$ = (10.04)(MSE)

5%, $SS_{.05}$ = (4.96)(MSE)

10%, $SS_{.10}$ = (3.29)(MSE)

Plan 6.1 Six factors - One split

All main effects except F are estimable

All two factor interactions are estimable

(1)		f	
ce	ae	abef	abdf
de	abcd	af	bf
acde	abde	abcdef	bdef
(1)	bc	bcdf	acdf
bd	ac	adef	ef
ab	abce	acef	cdef
bcde	be	cf	df
ad	cd	bcef	abcf

Error Degrees of Freedom = 10

Example:

Factor		Absent	Letter Present
a	Variety	Standard	Improved
b	Nitrogen	None	50 kg/ha
c	Potassium	None	20 kg/ha
d	Phosphorus	None	50 kg/ha
e	Weed control	None	Herbicide
f	Irrigation	None	Once

Six Factors - One split

Analysis Work Sheet

Treat.	Yield	I	II	III	IV	V	Effect	SS
(1) af							Total A	
bf ab							B AB	
cf ac							C AC	
bc abcf							BC **	
df ad							D AD	
bd abdf							BD **	
cd acdf							CD **	
bcdf abcd							** EF	
ef ae							E AE	
be abef							BE **	
ce acef							CE **	
bcef abce							** DF	
de adef							DE **	
bdef abde							** CF	
cdef acde							** BF	
bcde abcdef							AF Block	——

** Combine for error (10 d.f.)

$SS = (V)^2/32$

$SSE = \sum(SS^{**})$

$MSE = SSE/10$

$\bar{\bar{y}} = Total/32$

$\epsilon_k = E_k/32$, where E_k = Entry in V for effect K.

Minimum SS_α for significance

1%, $SS_{.01} = (10.04)(MSE)$

5%, $SS_{.05} = (4.96)(MSE)$

10%, $SS_{.10} = (3.29)(MSE)$

Plan 6.2 Six Factors - Two splits

All main effects except E and F are estimable.

All two-factor interactions except EF are estimable.

(1)	e	f	ef
ad	ce	abcf	abcdef
cd	abce	bf	bcef
ac	be	abdf	cdef
bd	acde	af	acef
abcd	bcde	df	ef
(1)	de	acdf	adef
bc	abde	bcdf	bdef
ab	ae	cf	abef

Degrees of Freedom for error = 10

Example

Factor		Absent	Present
		Letter	
a	Variety	Standard	Improved
b	Nitrogen	None	50 kg/ha
c	Phosphorus	None	50 kg/ha
d	Weed control	None	Herbicide
e	Planting date	Early	Late
f	Irrigation	None	Once

Six Factors - Two splits

Analysis Work Sheet

Treat.	Yield	I	II	III	IV	V	Effect	SS
(1) af							Total A	
bf ab							B AB	
cf ac							C AC	
bc abcf							BC **	
df ad							D AD	
bd abdf							BD **	
cd acdf							CD **	
bcdf abcd							** Block	
ef ae							Block AE	
be abef							BE **	
ce acef							CE **	
bcef abce							** DF	
de adef							DE **	
bdef abde							** CF	
cdef acde							** BF	
bcde abcdef							AF Block	

**		Combine for error (10 d.f.)
SS	=	$(V)^2 / 32$
SSE	=	$\sum$ (SS**)
MSE	=	SSE/10
$\bar{\bar{y}}$	=	Total /32
e_k	=	E_k /32, where E_k = Entry in V for effect K

Mininum SS_α for significance

1%, $SS_{.01}$ = (10.04)(MSE)

5%, $SS_{.05}$ = (4.96)(MSE)

10%, $SS_{.10}$ = (3.29)(MSE)

Plan 6.3 Six Factors - Three splits

All main effects except D, E, and F are estimable.

All two-factor interactions except DE, DF, and EF are estimable.

	bc	ce	abcf	bcef
(1)	(1)	ae	cf	ef
	ac	abce	af	acef
	ab	be	bf	abef
	abcd	acde	bcdf	bdef
d	ad	de	abdf	abcdef
	cd	abde	df	cdef
	bd	bcde	acdf	adef
	(1)	e	f	ef

Degrees of Freedom for error = 9

Example:

Factor		Absent	Letter	Present
a	Variety	Standard		Improved
b	Nitrogen	None		50 kg/ha
c	Weed Control	None		Herbicide
d	Planting Method	Broadcast		Drill
e	Planting Date	Early		Late
f	Irrigation	None		Once

Six Factors - Three splits

Analysis Work Sheet

Treat.	Yield	I	II	III	IV	V	Effect	SS
(1) af							Total A	——
bf ab							B AB	
cf ac							C AC	
bc abcf							BC Block	——
df ad							Block AD	
bd abdf							BD **	
cd acdf							CD **	
bcdf abcd							** Block	——
ef ae							Block AE	
be abef							BE **	
ce acef							CE **	
bcef abce							** Block	——
de adef							Block **	
bdef abde							** CF	
cdef acde							** BF	
bcde abcdef							AF Block	——

** Combine for error (9 d.f.)

$SS = (V)^2/32$

$SSE = \sum (SS^{**})$

$MSE = SSE/9$

$\bar{\bar{y}} = \text{Total}/32$

$e_k = E_k/32$, where E_k = Entry in V for effect K.

Minimum SS_α for significance

1%, $SS_{.01} = (10.56)(MSE)$

5%, $SS_{.05} = (5.12)(MSE)$

10%, $SS_{.10} = (3.36)(MSE)$

<u>Data Analysis :</u> It is not necessary to complete an analysis of variance table for these plans. The required computations and significance tests may be done on the work sheet which accompanies each plan. The computations proceed as follows:

1. Enter yields in the "yield" column on the work sheet. Be sure that the yields correspond to the treatments listed in the first column.
2. Add the first two yields to obtain the first entry in column I. Add the third and fourth yields to get the second entry in column I. Continue in this way adding successive pairs of yields until the top half of column I has been filled. (All pairs have been added).
3. Subtract the first yield from the second to obtain the next entry in column I. Subtract the third yield from the fourth to get the next entry. Continue in this way subtracting the first from the second member of each successive pair until the bottom half of column I has been filled. (Differences of all pairs have been obtained).
4. To obtain the entries in column II repeat steps 2. and 3. using the entries in column I.
5. For column III repeat steps 2. and 3. using the entries in column II.
6. Continue in this way filling successive columns until column V has been filled.

The first entry in column V is the sum of all yields in the experiment. The other entries are the totals for the main effects, interactions, error, and blocks. These are identified by the symbols in the "effects" column.

Now compute a sum of squares (SS) for each entry except the effects labelled "Total" and "Block". These are computed as follows:

$$SS_k = E_k^2 / 32$$

where E_k is the entry in V for effect K. Each of these sums of squares has one degree of freedom.

The error sum of squares (SSE) is obtained by adding together all of the sums of squares indicated by a double asterisk (**). The degrees of freedom, d.f.E., for SSE is the number of sums of squares added to obtain SSE. This is given for each plan. The error mean square (MSE) is computed as

$$MSE = SSE / d.f.E$$

The significance of each main effect and interaction may be tested using the ratio

$$F = SS_k / MSE$$

this ratio has one degree of freedom for the numerator and d.f. E degrees of freedom for the denominator . The significance of each effect is determined by comparing the calculated F with the F in the standard tables. If the calculated F is larger than F the effect is significant.

An equivalent, but simpler, procedure can be derived by substituting F into the F ratio and solving for the mininum sum of squares, SS , required for significance at the α % level. This is obtained as

$$F_\alpha = SS_\alpha / MSE$$

$$SS_\alpha = (F_\alpha)(MSE)$$

where F_α is taken from the α level F table with one and d.f. E degrees of freedom. The value of SS_α at the 1%, 5%, and 10% level is given for each plan.

Presentation of Results: The results of the trial may be presented in tables of means, which should be included only for those factors for which the effect is significant. If an interaction is significant the main effects of the interacting factors have no meaning regardless of whether or not they are significant. In this case, the results are presented in a two-way table of means. If the interactions are not significant the results may be presented in one-way tables of means for the significant effects.

To illustrate the construction of these tables, suppose that the AB interaction is significant, and that the main effect of C is significant while none of the interactions of C with other factors is significant. The effect totals in column V are used in computing the means.

First compute the grand mean, $\bar{\bar{y}}$, of the experiment as

$$\bar{\bar{y}} = (\text{Total}) / 32$$

then compute the effect, e_k. of each of the main effects and interactions whose tables are being constructed. For the illustration being considered we require:

$$e_A = E_A / 32$$
$$e_B = E_B / 32$$
$$e_{AB} = E_{AB} / 32$$
$$e_C = E_C / 32$$

where E_k is the entry in column V corresponding to the effect required.

The two-way table of means for the AB interaction is

B	A Low	High
Low	(-A-B)	(+A-B)
High	(-A+B)	(+A+B)

In which

$$-A-B = \bar{\bar{y}} - e_A - e_B + e_{AB}$$

$$+A-B = \bar{\bar{y}} + e_A - e_B - e_{AB}$$

$$-A+B = \bar{\bar{y}} - e_A + e_B - e_{AB}$$

$$+A+B = \bar{\bar{y}} + e_A + e_B + e_{AB}$$

and - indicates the mean with the factor at the low level, while + indicates the mean with the factor at the high level. The standard error, s_{AB}, of these means is

$$s_{AB} = \sqrt{MSE/8}$$

The one-way table of factor C means is

Factor C	Low	High
Mean	- C	+ C

in which

$$-C = \bar{\bar{y}} - e_c$$

$$+C = \bar{\bar{y}} + e_c$$

the standard error of these means, s_c, is

$$s_c = \sqrt{MSE/16}$$

Numerical Example: An experiment was conducted to determine the effect of several factors on the yield of barley. Six factors were tested, each at two levels. The factors and their assignment to the two levels were

Factor		Absent	Letter	Present
a	Nitrogen	None		50 kg/ha
b	Phosphorus	None		20 kg/ha
c	Weed Control	None		Herbicide
d	Seed Rate	Light		Heavy
e	Minor Elements	None		2 kg/ha
f	Planting Date	Early		Late

To facilitate the management of the trial it was decided to split the experiment and plant one half on the early date and the other half on the late date. The experiment was conducted according to Plan 6.1.

The field plan and yields (kg/decare) were as follows:

ce 119	ae 133	abef 138	abdf 135
de 122	abcd 144	af 155	bf 113
acde 156	abde 124	abcdef 146	bdef 128
(1) 138	bc 95	bcdf 116	acdf 152
bd 106	ac 170	adef 150	ef 116
ab 131	abce 181	acef 172	cdef 122
bcde 148	be 106	cf 108	df 103
ad 146	cd 137	bcef 114	abcf 172
Early		Late	

Six Factors - One split

Analysis Work Sheet

Treat.	Yield	I	II	III	IV	V	Effect	SS
(1)	138	293	537	1082	2121	4296	Total	———
af	155	244	545	1039	2175	514	A	8,256.12 1
bf	113	278	490	1079	289	-102	B	325.12
ab	131	267	549	1096	225	- 24	AB	18.00
cf	108	249	493	174	-97	208	C	1,352.00 5
ac	170	241	586	115	- 5	154	AC	741.12 10
bc	95	289	524	169	15	62	BC	120.12
abcf	172	260	572	56	-39	36	**	40.50
df	103	249	35	-60	67	- 26	D	21.12
ad	146	244	139	-37	141	-172	AD	924.50 10
bd	106	291	72	- 1	75	20	BD	12.50
abdf	135	295	43	- 4	79	-114	**	406.12
cd	137	272	49	16	17	6	CD	1.12
acdf	152	252	120	- 1	45	-196	**	1,200.50
bcdf	116	278	24	29	41	- 32	**	32.00
abcd	144	294	32	- 68	- 5	10	EF	3.12
ef	116	17	-49	8	-43	54	E	91.12
ae	133	18	-11	59	17	-64	AE	128.00
be	106	62	- 8	93	-59	92	BE	264.50
abef	138	77	-29	48	-113	-54	**	91.12
ce	119	43	- 5	104	23	74	CE	171.12
acef	172	29	4	- 29	- 3	4	**	.50
bcef	114	15	-20	71	17	28	**	24.50
abce	181	28	16	8	- 97	-46	DF	66.12
de	122	17	1	38	51	60	DE	112.50
adef	150	32	15	- 21	- 45	- 54	**	91.12
bdef	128	53	-14	9	-133	-26	**	21.12
abde	124	67	13	36	- 63	-80	CF	200.00
cdef	122	28	15	14	- 59	-96	**	288.00
acde	156	- 4	14	27	27	70	BF	153.12
bcde	148	34	-32	- 1	13	86	AF	231.12
abcdef	146	- 2	-36	- 4	- 3	-16	Block	———

** Combine for error (10.d.f.)

$SS = (V)^2/32$

$SSE = \sum(SS^{**}) = 40.50+406.12 +$
$+ 1200.50+32.00+91.12+.50 +$
$+ 24.50+91.12+21.12+288.00$
$= 2195.48$

$MSE = SSE/10 = 2195.48/10 = 219.55$

$\bar{\bar{y}} = Total/32 = 4296/32 = 134.25$

$e_k = E_k/32$

1 significant at the 1% level

5 significant at the 5% level

10 significant at the 10% level

minimum SS_α for significance

1%, $SS_{.01} = (10.04)(219.55) = 2,204.28$

5%, $SS_{.05} = (4.96)(219.55 = 1,088.97$

10%, $SS_{.10} = (3.29)(219.55) = 722.32$

Sample Calculations :

I.

293	=	138 + 155
244	=	113 + 131
⋮		
294	=	148 + 146
17	=	155 - 138
18	=	131 - 113
⋮		
-2	=	146 - 148

. . . V.

4296	=	2121 + 2175
514	=	289 + 225
⋮		
10	=	13 + (-3)
54	=	2175 - 2121
-64	=	225 - 289
⋮		
-16	=	-3 - 13

$SSA = (514)^2/32 = 8,256.12$

$SSB = (-102)^2/32 = 325.12$

⋮

$SSAF = (86)^2/32 = 231.12$

<u>Discussion:</u> The main effect of nitrogen(A) is highly significant. The main effect of weed control (C) is significant at the 5% level. Two interactions, nitrogen x Weed control (AC), and nitrogen x Seed rate (AD) are significant at the 10% level. Only the AD interaction approaches significance at the 5% level.

<u>Presentation of Results:</u>

We can summarise the results in two tables of means, A two-way table of nitrogen x seed rate means, and a one-way table of weed control means. For this purpose we require the following estimates of effects:

$$\bar{\bar{y}} = \text{Total}/32 = 4296/32 = 134.25$$
$$e_a = E_a/32 = 514/32 = 16.06$$
$$e_c = E_c/32 = 208/32 = 6.50$$
$$e_d = E_d/32 = -26/32 = -.81$$
$$e_{ad} = E_{ad}/32 = -172/32 = -5.38$$

The required summary tables are:

Table 1. Mean Yields of Barley (kg/Decare) at Different Rates of Nitrogen and Seeding.

	Nitrogen		
Seed Rate	None	50 kg/ha	Standard Error
Light	113.62	156.50	5.24
Heavy	122.76	144.12	

$$- A - D = \bar{\bar{y}} - e_a - e_d + e_{ad} = 134.25 - 16.06 -(-.81)+(-5.38)=113.62$$

$$- A + D = \bar{y} - e_a + e_d - e_{ad} = 134.25 - 16.06 +(-.81)-(-5.38) = 122.76$$

$$+ A - D = \bar{\bar{y}} + e_a - e_d - e_{ad} = 134.25 + 16.06 - (-.81)-(-5.38) = 156.50$$

$$+ A + D = \bar{\bar{y}} + e_a + e_d + e_{ad} = 134.25 + 16.06 +(-.81)+(5.38) = 144.12$$

$$\text{Standard error} = \sqrt{MSE/8} = \sqrt{219.55/8} = 5.24$$

Table 2. Mean Yields of Barley (kg/Decare) with and without weed control.

Weed Control	None	Herbicide	Standard Error
Mean	127.75	140.75	3.70

$$- c = \bar{\bar{y}} - e_c = 134.25 - 6.50 = 127.75$$

$$+ c = \bar{\bar{y}} + e_c = 134.25 + 6.50 = 140.75$$

$$\text{Standard Error} = \sqrt{MSE/16} = \sqrt{219.55/16} = 3.70$$