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The titles of the Technical Papers of the California Agricultural Experiment Station, which HILGARDIA replaces, and copies of which may be had on application to the Publications Secretary, Agricultural Experiment Station, Berkeley, are as follows:

4. Effect of Sodium Chlorid and Calcium Chlorid upon Growth and Composition of Young Orange Trees, by H. S. Reed and A. R. C. Haas. April, 1923.
5. Citrus Blast and Black Pit, by H. S. Fawcett, W. T. Horne, and A. F. Camp. May, 1923.
6. A Study of Deciduous Fruit Tree Rootstocks with Special Reference to Their Identification, by Myer J. Heppner. June, 1923.
7. A Study of the Darkening of Apple Tissue, by E. L. Overholser and W. V. Cruess. June, 1923.
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10. The Seasonal Variation of the Soil Moisture in a Walnut Grove in Relation to the Hygroscopic Coefficient, by L. D. Batchelor and H. S. Reed. September, 1923.
11. Studies on the Effects of Sodium, Potassium, and Calcium on Young Orange Trees, by H. S. Reed and A. R. C. Haas. October, 1923.
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17. Nutrient and Toxic Effects of Certain Ions on Citrus and Walnut Trees with Especial Reference to the Concentration and Ph of the Medium, by H. S. Reed and A. R. C. Haas. October, 1924.
18. Factors Influencing the Rate of Germination of the Seed of Asparagus Officinalis, by H. A. Borthwick. March, 1925.
19. The Relation of the Subcutaneous Administration of Living Bacterium Abortum to the Immunity and Carrier Problem of Bovine Infectious Abortion, by George H. Hart and Jacob Traum. April, 1925.
20. A Study of the Conductive Tissues in Shoots of the Bartlett Pear and the Relationship of Food Movement to Dominance of the Apical Buds, by Frank E. Gardner. April, 1925.

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VARIATION IN THE YIELDS OF FRUIT TREES IN RELATION TO THE PLANNING OF FUTURE EXPERIMENTS[1,2]

E. R. PARKER[3] AND L. D. BATCHELOR[4]

INTRODUCTION

The yields resulting from field trials have, in many cases, indicated the varying responses of plants to soil conditions which appear to be independent of the considerations of the trial. These normal fluctuations in yield constitute a source of experimental error to which all field trials are subject. They are of such importance that they must be taken into account in the planning of such experiments, as well as in the interpretation of the results.

In orchard trials such errors may be especially large. The great variation observed is due, in part, to the relatively large area of land involved in a single experiment, with the attendant possibilities of important changes in soil and topography. It is also due in some degree to the individuality of the trees. These two classes of factors ordinarily increase the observed variations greatly above those found in experiments with agronomic crops, for in the latter the use of a large number of plants in a single plot results in practical elimination of the effects of individual plant variation. In addition, the relatively small size of the plots permits them to be located on a small area of land. In the case of

[1] Received for publication December 28, 1931.

[2] Paper No. 256, University of California Graduate School of Tropical Agriculture and Citrus Experiment Station, Riverside, California.

[3] Assistant Horticulturist in the Citrus Experiment Station.

[4] Horticulturist in the Citrus Experiment Station, and Director, Graduate School of Tropical Agriculture and Citrus Experiment Station.

agronomic crops, significant correlations frequently exist between the yields of nearby plots.

Another very important source of error in the interpretation of the results of trials with trees is due to the long life of the plants. Since cultural treatments may have cumulative effects upon soils and trees, and since responses in various seasons may differ, it is obligatory that experiments be extended over a long period of time. Consequently, the same individual trees and plots are employed repeatedly in the experiment in the same manner. Any individuality of the material and of the soil finds expression year after year in about the same way. This results in correlations between observations in succeeeding years. In the case of trials with annual crops, however, this effect is largely eliminated by the use of different plants each year, and in many experiments by rearrangements of the location of the treatments during various years of the experiment.

In determining the relative effects of different treatments in any field trial, the ideal would be to ascertain the effect of the various treatments under absolutely identical conditions. In orchard work, such a situation is obviously impossible. The only possibility is to try each treatment simultaneously on a portion of the orchard. What is desired, then, is to obtain for each treatment a sample of the orchard which adequately "represents" the mean yield and variability of the entire orchard. The difficulties, as well as the importance, of obtaining such a sample have been demonstrated for orchard crops by the results of Batchelor and Reed[(4)] in their studies of the variability of several orchards.

Many methods have been proposed for correcting and interpreting the results of agronomic trials where there is doubt as to whether the individual plots represent a fair sample of the field as a whole. Most of these suggestions have been made as a result of studies upon uniformly planted and treated fields, where the effects of variability of the plants and soils could be studied in various years. Such studies have indicated that the extent and nature of the variations which have been observed differ in different plantings, and that each field presents some special problems. The variability of trees emphasizes the importance of similar observations in experimental orchards. It appears that each orchard used for experimental purposes should be individually studied.

It is the purpose of this study to determine, in part, the nature of the variations that exist in an experimental orchard which has been maintained a number of years under conditions of uniform culture. The bearing which this may have upon the efficacy of certain methods of interpreting the results of the trials to be made upon this orchard, in relation to the manner of laying out the experiment, will be touched upon. The plan of an experiment will also be presented, which, it is hoped, may throw some light upon the problems involved in field trials with orchard trees and upon methods of minimizing their seriousness.

MATERIAL

As a result of the studies of Batchelor and Reed[4] upon the variability of fruit trees, it appeared to them that observations might profitably be made upon the variability of trees destined for experimental use, while they are under a condition of uniform treatment, and prior to the beginning of the experiment. Therefore, in accordance with this idea and their other findings, an orchard of Washington Navel oranges was planted in 1917 at the University of California Citrus Experiment Station at Riverside. The ultimate purpose was to install a series of fertilizer trials in this orchard. The orchard was maintained under conditions of uniform culture for a period of ten years. The results of certain studies made upon data obtained from it are reported here.

Only a brief review of the plan and history of the experimental orchard is necessary for an understanding of the present paper. A more detailed account of the plan and history of the orchard has been published elsewhere by Batchelor, Parker, and McBride.[5]

In order to increase the accuracy of future trials, every practical means was employed to make the planting as uniform as possible. Land was selected which had been used for dry-farming grain culture from the time it was first cleared in 1875 until 1917, when the trees were planted. No leveling or grading was ever done purposely on this land.

Particular attention was paid to the selection of trees for this planting. Seedling rootstocks of sweet orange (*Citrus sinensis*) were used which had been culled three times to eliminate nonvigorous and undesirable types. The trees to form the experimental rows were budded to the Washington Navel variety. The buds were carefully selected from productive trees whose performance records were known.

Eight Washington Navel orange trees in a single row constitute a plot. A Valencia orange tree was planted as a border tree at the upper end of each plot row and a grapefruit tree at the lower end. Each two adjacent test rows of Navel oranges are separated by a guard row of Valencia oranges and grapefruit, which alternate in the guard row. Forty per cent of the trees are, therefore, test trees. The planting distance is 20 feet in the row and 24 feet between rows. Each test and each guard tree occupies 0.011 acre. Each plot treatment is extended to the middle of each adjoining guard row, and also 10 feet past the end guard trees so that the treated area for each plot is thus equal to that occupied by 20 trees, 9,600 square feet, or 0.22 acre. The 199 plots occupy 43.86 acres. The arrangement of the trees in the plots and guard rows is given

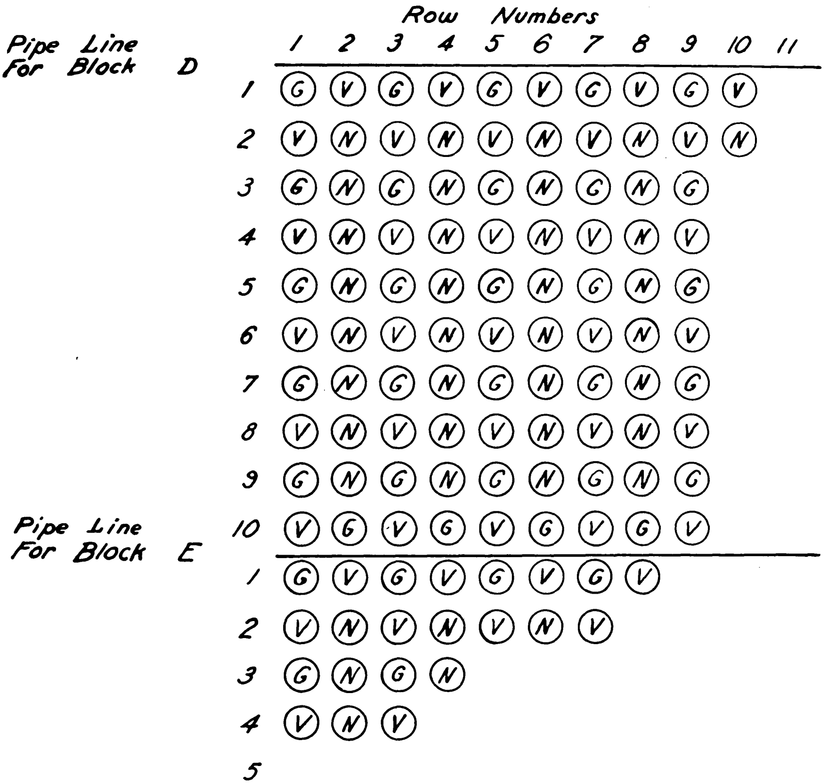

Fig. 1. Arrangement of trees in plot and guard rows. N = Washington Navel orange; V = Valencia orange; G = Marsh grapefruit.

in figure 1. In planting the trees, an effort was made to mix them so that trees from every section of the nursery should be planted at random in the orchard.

The plots were planted in 1917 in 10 blocks which are lettered from D to M inclusive. The blocks consist of 12 to 27 plots each. The plot rows are numbered with even numbers in each block while the guard rows are numbered with odd numbers. The arrangement of the blocks and plots is shown in figure 2.

The slope of the land averages 1.6 per cent, and is, on the whole, fairly uniform, as shown in figure 3.

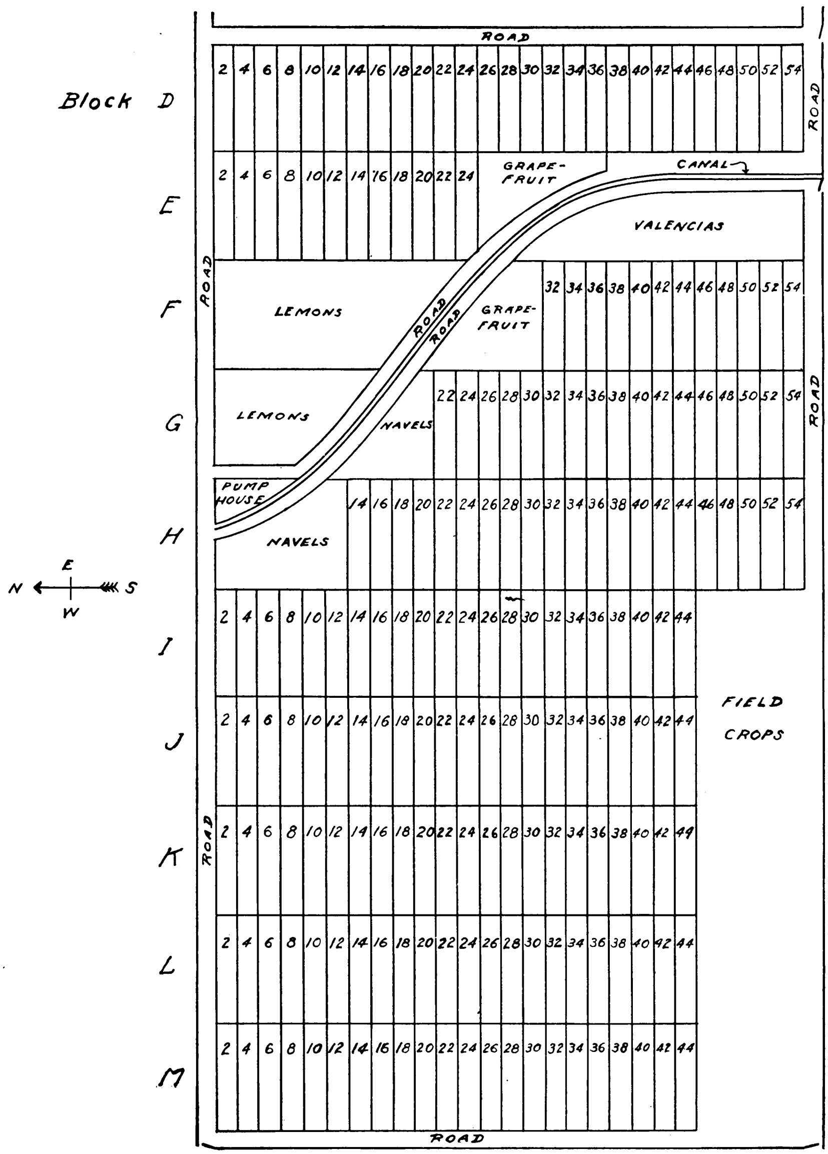

Fig. 2. Plan of experimental field showing arrangement of blocks and plots. (From Bul. 451.

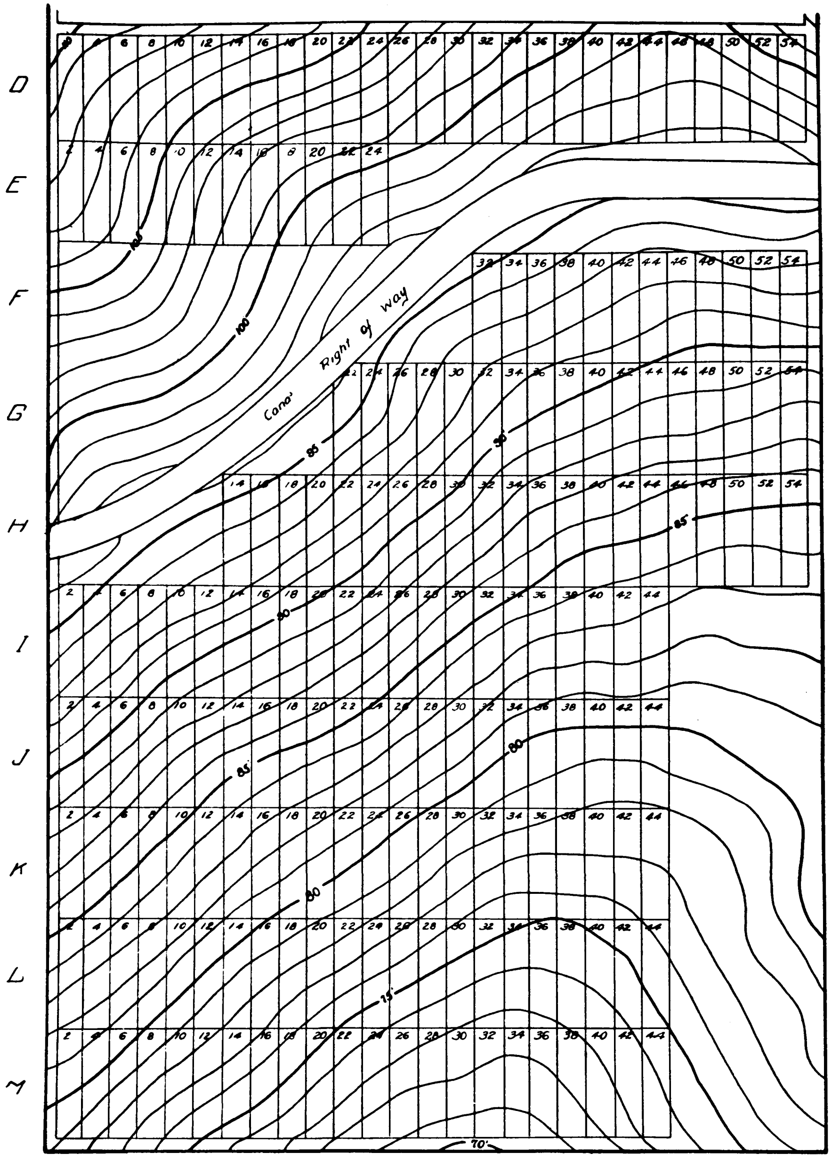

Fig. 3. Contour map of experimental area. Interval between contours equals 1 foot.

Irrigation systems have been installed so that each block is provided with a pipe line. This has made it possible to irrigate each block or even

TABLE 1

FREQUENCY DISTRIBUTION OF YIELDS OF INDIVIDUAL TREES FOR EACH YEAR, 1921 TO 1927*

Yield in pounds	Number of trees, 1921	Yield in pounds	Year					
			1922	1923	1924	1925	1926	1927
			Number of trees					
0–4	226	0–9	3					
5–9	168	10–19	9	9				
10–14	171	20–29	24	28			2	1
15–19	143	30–39	33	70		1	3	1
20–24	157	40–49	102	113	1	1	10	1
25–29	196	50–59	155	211	0	4	12	2
30–34	217	60–69	151	248	4	7	24	2
35–39	67	70–79	127	264	5	8	54	9
40–44	114	80–89	363	199	13	29	102	15
45–49	31	90–99	165	156	36	49	118	22
50–54	13	100–109	136	112	55	81	156	19
55–59	5	110–119	126	64	63	146	175	39
60–64	1	120–129	84	34	94	176	185	61
		130–139	20	6	148	206	158	98
		140–149	14	2	175	216	151	117
		150–159	2		167	191	109	134
		160–169	1		185	172	72	185
		170–179			157	114	54	184
		180–189			150	63	42	178
		190–199			96	27	36	143
		200–209			83	18	22	125
		210–219			40	7	20	79
		220–229			27	3	6	53
		230–239			8		2	26
		240–249			5		2	8
		250–259			0		2	9
		260–269			0			5
		270–279			1			
		280–289			1			
		290–299			2			
		300–309			0			
		310–319			1			
Total	1,509	Total	1,515	1,516	1,517	1,519	1,517	1,516
Mean yield per tree	*pounds* 20.91 ±0.234		*pounds* 82.25 ±0.453	*pounds* 73.44 ±0.404	*pounds* 158.99 ±0.576	*pounds* 141.45 ±0.482	*pounds* 127.55 ±0.617	*pounds* 170.50 ±0.603

* Crop picked in the spring of years mentioned.

each row separately, according to the condition of the soil in the various sections of the field.

The entire orchard was maintained with uniform culture until the spring of 1927. During this preliminary period great care was taken to

TABLE 2

COEFFICIENTS OF VARIATION OF YIELDS OF INDIVIDUAL TREES

Year	Coefficient of variation, per cent
1921	64.35±1.07
1922	31.79±0.43
1923	31.78±0.43
1924	20.93±0.27
1925	19.71±0.25
1926	27.93±0.37
1927	20.41±0.26

TABLE 3

MEAN YIELD IN POUNDS PER TREE FOR EACH PLOT, 1921

Plot	Blocks									
	M	L	K	J	I	H	G	F	E	D
2	18	34	27	28	15				9	25
4	22	35	19	22	40				7	24
6	29	36	35	24	40				12	19
8	14	36	34	24	31				15	15
10	23	31	20	14	16				19	12
12	30	16	25	28	12				13	17
14	12	23	32	32	13	15			17	19
16	19	30	27	21	14	19			13	20
18	15	33	27	32	20	23			13	6
20	16	22	24	28	15	21			9	18
22	15	31	19	28	28	20	10		19	11
24	25	*	21	34	22	17	18		24	20
26	20	25	28	36	23	28	19			14
28	23	24	24	37	20	29	18			18
30	32	28	32	36	37	38	24			21
32	30	33	29	23	21	26	18	23		18
34	22	*	29	34	12	27	25	19		15
36	20	27	31	15	27	25	20	14		12
38	18	22	17	24	16	23	20	15		17
40	20	22	24	20	26	37	22	13		7
42	21	25	27	28	26	25	32	16		5
44	14	17	21	31	24	†	21	23		5
46						15	16	11		6
48						15	11	7		4
50						13	10	8		5
52						16	12	4		7
54						5	‡	*		7

* Plots omitted because of injury to trees.

† Omitted from present calculations because of injury.

‡ Fruit stolen.

give all trees the same attention. The various orchard practices were carried out with moderation. Pruning was very light, only enough being done to build trees of good structure and to remove dead wood. Considerable attention was paid to the elimination of accidental factors which might affect yield. Careful examinations of all trees were made periodically for accidental defects and disease. In addition, study was

TABLE 4

MEAN YIELD IN POUNDS PER TREE FOR EACH PLOT, 1922

Plot	Blocks									
	M	L	K	J	I	H	G	F	E	D
2	66	88	75	89	90				41	71
4	76	86	79	82	112				36	64
6	87	97	81	82	123				47	64
8	51	93	80	93	104				66	68
10	69	92	91	83	91				63	68
12	86	75	100	120	85				60	63
14	55	82	111	108	75	100			65	73
16	66	95	106	89	83	104			63	77
18	59	96	97	102	89	105			59	49
20	59	73	95	106	85	98			44	66
22	60	95	93	98	105	76	75		57	55
24	68	*	82	103	82	89	97		74	73
26	58	85	78	108	93	101	77			75
28	72	72	78	115	88	115	103			58
30	84	88	97	105	114	125	95			82
32	78	86	102	84	78	107	80	111		77
34	62	*	87	108	68	104	100	93		72
36	77	93	91	81	117	101	84	93		67
38	70	72	61	70	87	99	96	88		88
40	75	76	80	68	90	110	94	82		58
42	68	80	92	92	93	94	105	98		57
44	62	79	78	64	83	†	93	104		58
46						86	97	91		46
48						88	84	91		51
50						83	79	82		61
52						83	89	78		62
54						65	66	*		47

* Plots omitted because of injury to trees.

† Omitted from present calculations because of injury.

undertaken to analyze the causes of the differences in yields which were recorded. This consisted of systematic soil surveys, studies on soil moisture, determination of soil nitrates, and inspection for differences in relative infestation of the citrus nematode *Tylenchulus semipenetrans,* in high and low-yielding plots. None of these factors was considered to be the primary cause of the variations in yield.

During the period until the Washington Navel orange crop was harvested in the spring of 1927, the responses of the test trees were measured by three criteria. These were: (1) the volume of the top of the tree expressed in cubic feet (determined by a canvas drawn over the top of the tree); (2) the area of the cross section of the trunk of the tree at a marked point; and (3) the yield of the trees. The yields during the first two years, 1921 and 1922, were taken carefully on a volume basis. One-tenth of a picking box was used as a unit. This value was later multiplied by the average value for the weight of this volume of fruit (4.244 pounds) so that the yield might be expressed in pounds. Beginning with 1923, the total amount of fruit produced by each tree, including windfalls, was weighed.

TABLE 5

MEAN YIELD IN POUNDS PER TREE FOR EACH PLOT, 1923

Plot	Blocks									
	M	L	K	J	I	H	G	F	E	D
2	50	76	60	72	63				61	84
4	66	58	72	63	62				84	100
6	74	65	52	56	79				78	89
8	52	60	42	66	68				86	71
10	65	73	65	73	55				82	78
12	71	59	72	79	55				103	87
14	46	75	85	86	51	54			96	103
16	57	51	83	74	75	56			73	78
18	47	61	64	75	60	58			77	62
20	62	62	72	81	68	65			65	51
22	66	107	80	91	86	65	65		64	65
24	82	*	58	56	86	59	60		75	62
26	69	87	56	62	64	63	46			62
28	75	83	95	93	75	78	88			58
30	55	92	114	72	103	83	92			79
32	74	84	95	83	81	76	88	72		85
34	56	*	89	78	69	73	75	48		75
36	77	85	90	93	104	83	73	54		86
38	77	78	68	69	88	82	90	59		89
40	80	69	85	87	82	89	72	56		83
42	82	65	86	84	86	84	86	70		76
44	70	69	73	72	58	†	73	102		79
46						49	75	72		89
48						59	78	74		67
50						67	81	63		61
52						46	90	79		75
54						67	79	*		59

* Plots omitted because of injury to trees.

† Omitted from present calculations because of injury.

The yields for the period of seven years, 1921 to 1927 inclusive, were obtained prior to the time of applying the various fertilizer treatments in 1927. Considering the field as a uniformity, or blank, experiment, the data have been subjected to a study of some factors which might influence the accuracy of the future trials.

The records of all normal trees of the same age are recorded for the purpose of this study. Certain trees, during the course of ten years, have naturally suffered from accidental causes, particularly from gopher injury, trunk and root diseases, and cultivation accidents. Some of these trees have been replaced by young ones, the records of which are omitted here. Others have recovered to a normal condition and their

TABLE 6

MEAN YIELD IN POUNDS PER TREE FOR EACH PLOT, 1924

Plot	Blocks									
	M	L	K	J	I	H	G	F	E	D
2	105	133	120	136	149				140	165
4	109	114	145	126	145				198	184
6	142	132	135	125	162				179	209
8	104	130	118	149	171				189	179
10	119	138	142	135	146				179	180
12	114	127	140	161	151				189	191
14	113	146	169	158	143	175			177	203
16	127	154	165	161	153	175			120	138
18	110	126	138	153	156	173			159	142
20	122	146	159	171	165	181			151	141
22	124	179	163	179	183	156	171		161	159
24	138	*	153	141	158	153	167		152	141
26	122	145	120	127	147	147	131			157
28	143	154	164	166	172	186	199			155
30	129	166	190	162	196	203	182			174
32	149	155	167	168	162	160	186	189		188
34	142	*	172	158	142	181	174	150		157
36	153	172	187	193	186	185	174	162		171
38	143	167	146	159	172	179	192	159		148
40	134	158	158	176	175	191	177	157		160
42	128	140	189	178	177	178	193	180		158
44	117	137	172	171	153	†	191	198		181
46						159	184	184		188
48						150	190	177		149
50						168	172	163		136
52						147	191	193		160
54						157	182	*		140

* Plots omitted because of injury to trees.

† Omitted from present calculations because of injury.

records, which were temporarily excluded from the calculations, are included in the later years. All obvious cases of bud-mutation have been eliminated. The elimination of the records of 7 abnormal trees, only, has been necessitated by factors of an unknown nature. The effect of deletion of the yield of abnormal trees upon total plot yield has been compensated for by considering the plot yields on the basis of mean yields per tree. This procedure gives equal weight to the records of individual plots when they are combined.

When there were more than 4 abnormal trees in any one plot, the entire plot was eliminated from the records for the purposes of the present study. Four plots were eliminated for this reason during the entire period, and in addition, 1 plot was eliminated in the year 1921 because of the theft of the matured fruit. Two plots contain only 4

TABLE 7

MEAN YIELD IN POUNDS PER TREE FOR EACH PLOT, 1925

Plot	Blocks									
	M	L	K	J	I	H	G	F	E	D
2	121	138	125	128	145				109	115
4	116	135	136	125	151				152	150
6	129	132	136	114	171				120	138
8	95	126	121	140	164				156	148
10	115	120	128	124	145				138	138
12	113	134	129	145	141				160	148
14	107	158	149	149	131	168			129	136
16	119	143	143	134	123	161			105	101
18	105	133	130	122	135	145			138	102
20	106	132	136	155	135	151			124	103
22	109	141	148	144	153	127	140		142	139
24	115	*	133	127	116	139	145		135	115
26	101	116	106	108	116	120	116			151
28	131	128	143	136	149	158	161			126
30	121	147	159	140	155	181	159			152
32	138	146	151	158	140	142	151	201		150
34	129	*	153	150	134	170	155	155		125
36	157	163	174	175	158	168	149	175		146
38	133	153	138	156	152	165	170	159		144
40	137	153	156	166	171	174	158	160		116
42	127	143	187	170	157	160	164	165		158
44	126	142	157	166	140	†	152	179		164
46						138	166	171		141
48						140	168	163		129
50						153	147	153		117
52						137	175	170		124
54						123	149	*		115

* Plots omitted because of injury to trees.
† Omitted from present calculations because of injury.

normal trees, 1 contains 5, from 5 to 7 plots contain 6 in various years, and from 18 to 22 contain 7, while from 164 to 167 plots contain the full number, 8 trees.

STUDIES OF VARIABILITY OF YIELDS

Munson [36, 37] was among the earliest investigators to call attention to the marked difference in the yield of trees given the same cultural care. More recently the extent of the normal variation existing in uniformly treated orchards has been studied statistically by several authors. Among these are Pickering,[39] Batchelor and Reed,[4] Sax and Gowen,[48] Grantham and Knapp,[14] Anthony and Waring,[3] and Gadd.[13] Although the plantings studied have generally been selected for experimental purposes, and many of them have probably been more uniform than the average of commercial orchards, the results obtained

TABLE 8

MEAN YIELD IN POUNDS PER TREE FOR EACH PLOT, 1926

Plot	Blocks									
	M	L	K	J	I	H	G	F	E	D
2	72	81	86	90	103				113	133
4	75	93	111	98	106				128	152
6	96	78	95	103	119				115	141
8	62	109	84	110	107				143	144
10	77	92	97	109	126				134	134
12	93	93	114	131	113				122	126
14	79	107	121	122	101	123			125	137
16	75	85	107	110	106	101			97	101
18	75	95	99	110	116	126			131	115
20	85	105	115	131	127	112			121	109
22	94	124	122	122	136	112	110		120	124
24	103	*	112	103	93	87	109		117	128
26	97	118	96	93	95	89	77			150
28	108	121	115	107	117	110	126			133
30	94	129	141	124	151	133	143			143
32	126	135	130	128	117	115	133	156		154
34	146	*	151	128	128	129	140	130		148
36	160	164	142	155	132	128	130	148		152
38	129	166	128	135	141	141	155	135		146
40	139	156	149	156	144	150	126	141		147
42	122	142	185	154	146	152	179	192		182
44	125	139	171	153	139	†	170	199		165
46						148	199	212		195
48						163	180	161		153
50						167	189	169		142
52						136	177	185		145
54						152	180	*		133

* Plots omitted because of injury to trees.
† Omitted from present calculations because of injury.

have caused these authors to emphasize the magnitude of chance variations. The results also show that the extent of fortuitous variations is itself very different in the various orchards. Thus the coefficient of variation of individual trees has been reported to lie within the extremely broad range from 19.66 per cent (73 Jonathan apple trees for thirteen years, data of Anthony and Waring[3]) to 89.6 per cent (882 Ben Davis apple trees for 1918 only, reported by Sax and Gowen[48]). The majority of the coefficients given by Batchelor and Reed,[4] and by Anthony and Waring,[3] lie between 30 and 50 per cent. The limited data of this nature which are available suggest that the extent of variation fluctuates within different limits for each planting in various seasons. A knowledge of the characteristics of each orchard would apparently, therefore, be an aid in the planning of experimental work and the interpretation of the results obtained.

TABLE 9

MEAN YIELD IN POUNDS PER TREE FOR EACH PLOT, 1927

Plot	Blocks									
	M	L	K	J	I	H	G	F	E	D
2	108	104	107	103	128				138	159
4	128	152	169	129	144				165	188
6	136	153	156	114	183				156	204
8	107	153	146	129	157				192	210
10	145	162	174	135	168				184	169
12	134	168	179	134	132				206	184
14	159	186	186	145	146	170			203	173
16	154	167	170	144	140	182			139	145
18	159	180	145	152	164	186			179	160
20	152	177	187	164	167	181			189	157
22	135	180	185	186	163	162	161		187	199
24	114	*	186	185	154	158	159		157	209
26	135	173	168	160	186	171	172			183
28	183	157	181	177	172	180	166			165
30	167	164	186	174	193	194	168			188
32	195	158	165	185	178	172	159	180		178
34	177	*	190	182	187	176	163	191		188
36	188	202	193	186	203	193	152	193		191
38	170	186	172	155	177	187	185	171		181
40	160	217	182	180	187	188	168	187		168
42	154	198	205	195	204	183	205	214		198
44	141	189	206	181	181	†	185	210		219
46						178	209	201		216
48						174	197	173		162
50						163	184	156		172
52						136	179	187		168
54						118	160	*		152

* Plots omitted because of injury to trees.

† Omitted from present calculations because of injury.

VARIABILITY OF TREE YIELDS

The frequency distributions of yields of single trees of the planting under consideration are given in table 1 for the years 1921 to 1927 inclusive. During 1921 the trees produced the initial crop. Many trees produced less than 10 pounds per tree, and a considerable proportion of the trees produced nothing. (See table 3.) Inspection of table 1 indicates that in each year, except 1921, distributions were obtained which approach the distribution of the normal curve. In the years

1922 to 1927 inclusive, the application of the methods of statistics, based upon the assumption of a normal distribution to the problems undertaken, is apparently valid.

The coefficients of variation for annual yields of single trees in the seven years are given in table 2. In calculating them, the usual formula[5] for the coefficient was used, regardless of the type of the frequency distribution.

The first striking fact noted is, perhaps, the extremely large amount of variation of yields during the first year, 1921. In subsequent years the coefficients are less than half that of the first year. A tendency for the coefficients to be smaller after the third crop has been harvested is also shown. With the exception of 1926, the coefficients are about equal for the last four years of the period. The year 1926 was one of rather small crops, and it is probable that the influences reducing the size of crop that year may have been effective in increasing the variation.

If the coefficients for the year 1921 are excluded, the mean of the constants for the remaining six years is 25.4 per cent. In most of the orchards for which data on variability are available, the trees have been adjacent to each other. Although planting distances have varied in such trials, the trees have usually been larger and had a more extensive root system, so that the actual areas between test trees may have been comparatively small. In the present case, however, the field covers a relatively large area, and the test trees are only 40 per cent of the entire number. It is logical to assume that the use of an increased area of land (necessitated by the use of guard rows) would ordinarily cause an increase in variation of the test trees, by virtue of this greater dispersion. The relatively low coefficients obtained, therefore, are considered as evidence indicating the effectiveness of the original plan and the management of the planting in obtaining an uncommonly uniform orchard.

VARIABILITY OF PLOT YIELDS

The mean yields per normal tree of each plot for the seven years, 1921 to 1927 inclusive, are given in tables 3 to 9. The frequency distributions of these mean yields are presented in table 10.

The type of distribution obtained for yields of the year 1921 on a plot basis (table 10) is markedly in contrast with that obtained on a

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$$C=\frac{\sqrt{\frac{\Sigma fd^2}{N}}}{M}\cdot 100;\ \text{while } E_c=\pm\frac{0.6745}{\sqrt{2N}}\,C\left[1+2\left(\frac{C}{100}\right)^2\right]^{\frac{1}{2}}$$

tree basis for the same year (table 1). It is evident that trees of zero or very low productivity were not as a rule grouped together in local areas.

For the years 1922 to 1927 inclusive, the distributions on a plot basis approach the distribution of the normal curve. The use of the usual

TABLE 10

FREQUENCY DISTRIBUTION OF YIELDS PER TREE PER PLOT FOR EACH YEAR, 1921 TO 1927

Mean yield per tree per plot, pounds	Number of plots, 1921	Mean yield per tree per plot, pounds	Year					
			1922	1923	1924	1925	1926	1927
			Number of plots					
0–4	2	30–39	1					
5–9	14	40–49	6	7				
10–14	24	50–59	13	28				
15–19	43	60–69	28	44			1	
20–24	48	70–79	33	53			8	
25–29	31	80–89	44	44			7	
30–34	20	90–99	36	11		1	19	
35–39	10	100–109	23	7	3	12	19	5
40–44	2	110–119	8	1	7	15	23	3
		120–129	3		14	29	32	4
		130–139			14	32	23	10
		140–149			30	35	23	10
		150–159			33	37	17	25
		160–169			24	18	8	30
		170–179			31	13	4	27
		180–189			22	2	6	48
		190–199			14	0	4	15
		200–209			3	1	0	13
		210–219					1	5
Total	194	Total	195	195	195	195	195	195
Mean yield per tree per plot	*pounds* 21.2±0.39	Mean yield per tree per plot	*pounds* 82.5± 0.87	*pounds* 73.0± 0.67	*pounds* 158.6± 1.10	*pounds* 141.3± 0.97	*pounds* 127.2± 1.39	*pounds* 170.1± 1.15

statistical methods is apparently justifiable with this material in these years. The distributions are not so smooth as the ones for the yields of individual trees in the same years (table 1), however, a condition which is probably due to the smaller number of individuals in the populations.

The extent of variation as measured by the coefficient of variation has been determined for the mean yield per tree for each plot, during the respective years. The constants obtained are presented in table 11. It may be noted that the coefficients show the same trend as those obtained for yields of single trees in the corresponding years (table 2). They are, however, all lower on a plot-mean basis than on the basis of individual trees.

If the yields of the trees were such that they were distributed at random throughout the orchard, the coefficient of variation of the plots (C_p) should tend to approximate the values given by the formula

$$C_p = \frac{C_t}{\sqrt{n}},$$

where n is the number of trees per plot and C_t the coefficient of variation of tree yields. The theoretical coefficients of variation calculated by this formula (table 11) may be compared with the values actually found. One may observe that in each year the actual variation is greater than the theoretical. From this it is evident that a degree of correlation exists between the yields of trees of the same plots, because of the influence of some factor which tends to equalize their yields.

It is possible to determine the extent of the correlation between yields of trees of the same plot by means of the formulas for intraclass correlation developed by Harris[(16)] for use as a criterion of the homogeneity of fields. Application of his formula[6] resulted in the constants recorded in table 12.

A very significant positive correlation is seen to exist between the yields of trees of the same plots in each year. The mean correlation for

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[6] On account of the varying number of trees in the plots the formula used was:

$$r_{p_1p_2} = \frac{\{[\Sigma(C_p^2) - \Sigma(p^2)] \div \Sigma[n(n-1)]\} - \bar{p}^2}{\sigma_p^2}$$

where

$$\bar{p} = \Sigma[(n-1)p] \div \Sigma[n(n-1)]$$

$$\sigma_p^2 = \frac{\Sigma[(n-1)p^2]}{\Sigma[n(n-1)]} - \left(\frac{\Sigma[(n-1)p]}{\Sigma[n(n-1)]}\right)^2$$

in which

$r_{p_1p_2}$ = mean correlation between the yields of trees of the same plot
C_p = total yield of plots
p = yield of individual trees
n = number of p in the proper plot
$\bar{p}$ = mean of yields of trees

The constants were calculated from actual values. It was originally thought that the process should be materially simplified and that they could be calculated from grouped data in which trees in plots of either 8, 7, 6, 5, or 4 trees each, were distributed separately, and plot yields were also so distributed. It was found, however, that grouping reduced values for σ_p^2 markedly, and values obtained for $r_{p_1p_2}$ were too high.

The coefficients for 1921 and 1922 were determined from records of yield based on a volumetric unit, since it was thought that the use of the factor in converting volume records to weight might have introduced a certain degree of correlation into the distributions. This appeared to be the case; for when the calculated weights were used, the values of $r_{p_1p_2}$ found were slightly, if not significantly, higher, being $+0.353 \pm 0.015$ for 1921, and $+0.298 \pm 0.016$ for 1922.

the seven years is + 0.332. The high correlation of + 0.537 ± 0.012 which existed in 1926, a year in which yields were below normal, suggests that the crop that year in the experimental orchard was influenced to an unusual extent by circumstances which affected some regions in the field more than it did others. Variation was also greater in 1926 than in any other year from 1923 to 1927.

TABLE 11

COEFFICIENTS OF VARIATION OF YIELDS OF PLOTS

Year	Observed coefficient of variation, per cent	Theoretical ($C_{tree} \div \sqrt{8}$) per cent
1921	37.51±1.45	22.75
1922	21.68±0.77	11.24
1923	19.03±0.67	11.24
1924	14.36±0.50	7.40
1925	14.15±0.49	6.97
1926	22.58±0.81	9.88
1927	13.95±0.49	7.22

TABLE 12

COEFFICIENTS FOR INTRACLASS CORRELATION* OF YIELD OF TREES WITHIN THEIR RESPECTIVE PLOTS

Year	Coefficient of correlation
1921	+0.316±0.016
1922	+0.269±0.016
1923	+0.132±0.017
1924	+0.340±0.015
1925	+0.370±0.015
1926	+0.537±0.012
1927	+0.359±0.015
Mean	+0.332

* Calculated according to Harris' formulas.

When the average coefficient of correlation (r) between the trees of the plots is known, it is possible to calculate the expected coefficient of variation of the plots (C_{C_p}) on the basis of the observed variation of the individual trees (C_p) as given in table 2. This has been done by means of the formula (after Yule[70] p. 286),

$$C_{C_p}^2 = \frac{C_p{}^2}{n}[1+(n-1)r],$$

using the coefficients noted above in table 12. The calculated values for the coefficient of variation are given in table 13. They differ slightly from the observed constants given in table 11, but are of the same order.

The correlations which exist between the yields of trees in the same plot emphasize the magnitude of systematic variation in the annual yields of the trees of this planting. As an effort was made to plant the trees at random, there appears to be no principal factor other than soil differences which would cause this type of correlated variation. The importance of soil variability is, therefore, stressed. In the Harris coefficients of intraclass correlation, there is a suggestion that this influence may be more apparent in some years than in others. It is reasonable to assume from this information that if some areas maintain more vigorous trees than others, they will not suffer to the same extent in years of climatic stress. Soil differences, therefore, may be relatively more effective in causing systematic variation under adverse conditions.

TABLE 13

CALCULATED COEFFICIENTS OF VARIATION OF PLOTS BASED UPON THE VARIABILITY OF INDIVIDUAL TREES AND THE INTRACLASS CORRELATION

Year	Coefficient of variation, per cent
1921	40.60
1922	19.08
1923	15.59
1924	13.60
1925	13.20
1926	21.54
1927	13.52

VARIATION IN DIFFERENT YEARS

The practical value of the uniformity experiment lies partly in the fact that it may disclose areas of land which are not fitted for experimental purposes. In the areas which are suitable, it may also give some knowledge of the variability existing during the period of observation. The application of the latter information to the future trials rests upon the assumption that the extent of the variation and hence, presumably, the nature of the variations, will tend to be approximately the same in different years or periods.

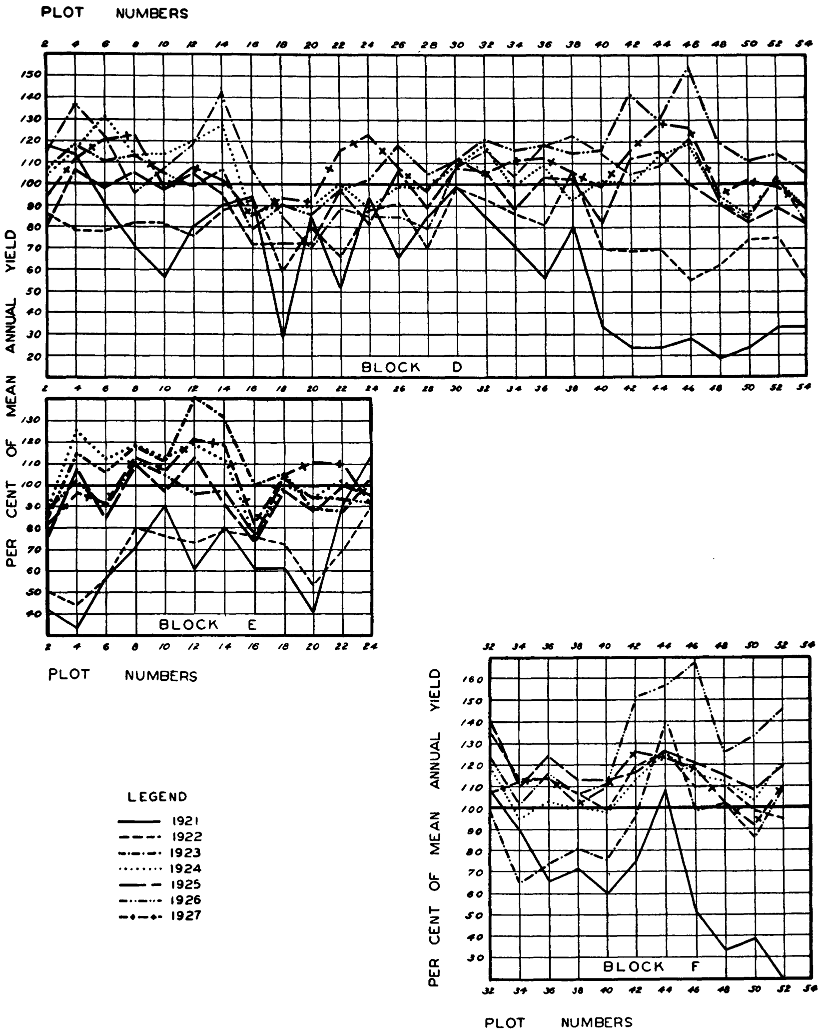

Fig. 4. Mean annual yield per tree for each plot in Blocks D, E, and F in percentage of the respective annual mean of the 195 plots of the orchard, for the years 1921 to 1927.

The data given for the variability of trees and plots of the orchard under discussion indicate, if the records of 1921 are not considered, that although there is some fluctuation in the coefficients of variation in individual years, there is a tendency for the annual gross variation to be of somewhat the same order. Similar conclusions were reached by Batchelor and Reed[(4)] and are made apparent by a study of the data of Sax and Gowen[(48)] on the variability of several orchards. The question

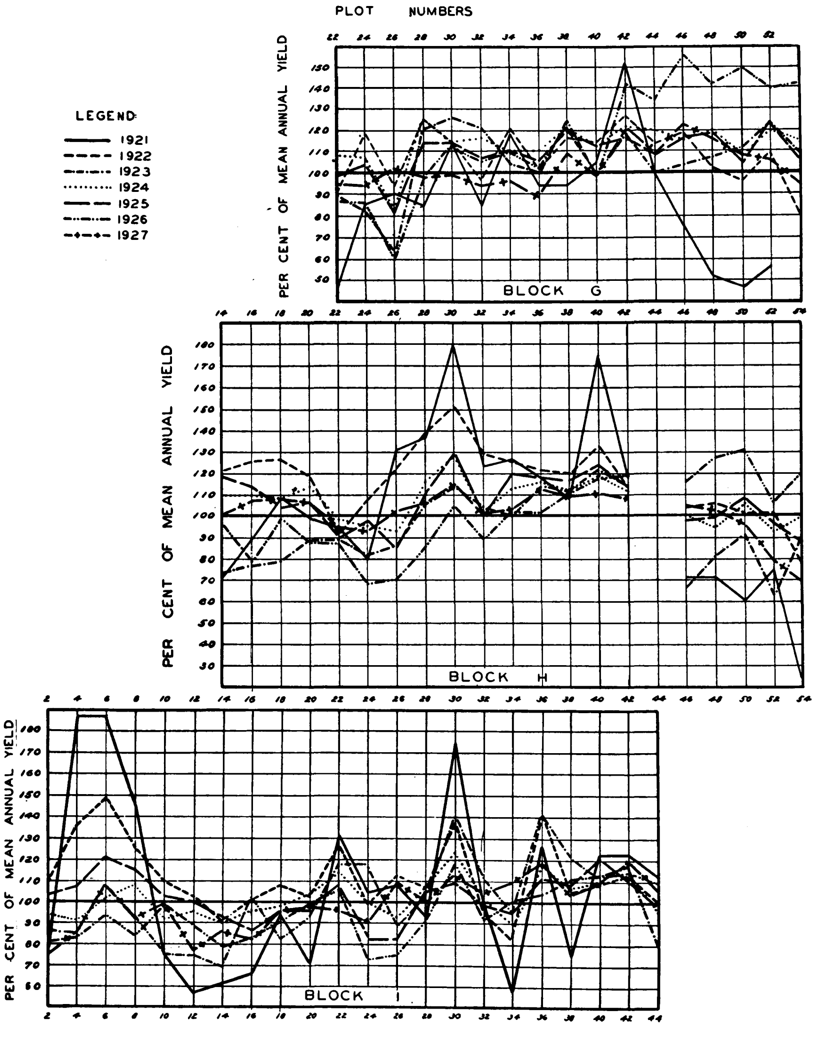

Fig. 5. Mean annual yield per tree for each plot in Blocks G, H, and I in percentage of the respective annual mean of the 195 plots of the orchard, for the years 1921 to 1927.

naturally arises as to whether this tendency towards somewhat constant gross variation is due to more or less consistent differences in relative yield of various plots and trees, or whether the individual fluctuations in yield are due to mere chance.

A comparison of the annual production of fruit of individual plots of all blocks of the orchard under discussion is given in figures 4, 5, and 6. In order to place the data on a comparable basis, the mean

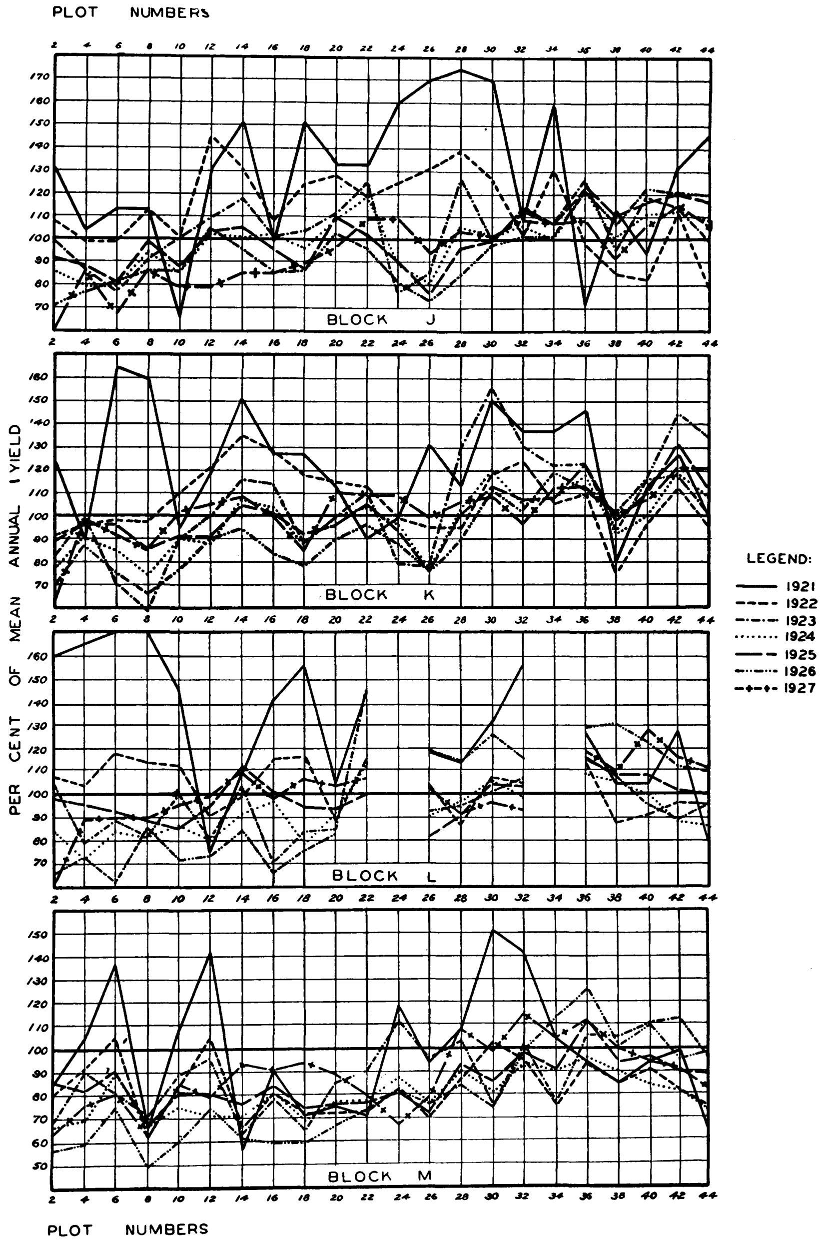

Fig. 6. Mean annual yield per tree for each plot in Blocks J, K, L, and M in percentage of the respective annual mean of the 195 plots of the orchard, for the years 1921 to 1927.

yields per tree of each plot are expressed in percentage of the mean yield per tree of all plots for the entire field for the proper year. With the exception of the yields of 1921, a tendency for individual plots to yield within a somewhat limited range is observed. This is particularly marked for the yields of 1924 to 1927 inclusive. The relative yields of the plots in 1922 and 1923 depart considerably from the values for later years, but these departures are of much less magnitude than those observed for the year 1921.

The tendency of the plots of this comparatively uniform orchard to yield about the same relative amount of fruit in the years 1922 to 1927 inclusive, can be emphasized by the calculation of the errors of the relative yields. Using the figures of the mean annual yield per tree per plot expressed in percentage of the mean plot yield of each year, which are plotted in figures 4, 5, and 6, the average probable error of the yield of a single plot in one year is given by the formula:

$$E_s = \pm 0.6745 \; \frac{\Sigma \left(\dfrac{\Sigma d^2}{n} - c^2 \right)^{1/2}}{N},$$

where

E_s = average probable error of the yield of a single plot about the mean yield of that plot in percentage of the mean annual plot yield

d = deviation of the yield of each plot in each year from the guessed mean percentage yield of that plot

c = correction to the guessed mean yield of the plot

N = number of plots (195)

n = number of years (6)

Calculation by the above formula, using the data indicated, shows that the average probable error of the yield of a single plot in any one year, around its own mean yield (E_s), equals 8.46 per cent of the mean yield of all plots. If the yields of all six years are combined to obtain the average probable error of the mean yield per tree for each plot for the six-year period, 1922 to 1927 inclusive, which may be called E_m, then, assuming a normal distribution, $E_m = \dfrac{8.06}{\sqrt{6}} = 3.29$ per cent of the mean plot yield for this period. With this information available, it is evident by inspection of figures 4, 5, and 6 that there is a tendency for the plots to yield about the same relative amounts, and that there were significant differences in mean yield between many of the plots during the preliminary period of testing.

For measuring the interannual relations between the responses of plants, Harris[15] has urged the use of the coefficient of correlation. Harris and Scofield[18, 19] have applied the method to the study of the permanence of yields of field crops. They find that in general there is a positive correlation between the yields of plots throughout a term of years, but that the correlation is influenced by weather conditions and by the nature of the rotation of the crops. Following the same procedure, Sax and Gowen[48] found that with apple trees on their experimental farm a high correlation exists between yields of the same trees over a period of five years. They reported similar findings as a result of studies of data of Hedrick and Anthony[21] for apples, and of data of Shamel, Scott, and Pomeroy[49, 50] for Washington Navel and for Valencia oranges. Collison and Harlan[8] have recently published similarly high interannual correlations in yield of trees of the experiment station at Geneva, New York.

TABLE 14

INTERANNUAL CORRELATION COEFFICIENTS FOR YIELDS OF INDIVIDUAL TREES

	1922	1923	1924	1925	1926	1927
1921	+0.637±0.010	+0.260±0.016	−0.173±0.017	+0.170±0.017	−0.171±0.017	−0.083±0.017
1922		+0.307±0.016	+0.324±0.016	+0.455±0.014	+0.069±0.017	+0.153±0.017
1923			+0.595±0.011	+0.415±0.014	+0.347±0.015	+0.255±0.016
1924				+0.685±0.009	+0.532±0.012	+0.468±0.014
1925					+0.550±0.017	+0.488±0.013
1926						+0.536±0.012

In order to determine the relation of the yield of one year to that of the other years for the present orchard, the possible interannual correlations of yield of individual trees have been calculated. These are presented in table 14.

With the exception of the yields of 1921 as compared with those of the other years, significantly positive correlations were found. Correlations involving yields of 1921 showed considerable irregularity, ranging from a very significant positive coefficient with yields of trees in 1922 to significant negative correlations in three of the subsequent years. No consistent relation of the yields of 1921 with those of later years is indicated by the data.

Correlations obtained for the yields of trees in 1922 with the yields in following years are all significantly positive, although one correlation (with the yields harvested in 1926) is relatively low, being only slightly larger than four times its probable error. All the possible correlations found for yields in 1923 with those of subsequent years are positive, high, and significant. There is a suggestion that the magnitude of the correlations decreases with time, however, for the correlations between yields of consecutive years were found to be largest, while the correlations decrease slowly as comparisons are drawn with more remote years. There are no irregularities of such magnitude as those noted for correlations involving yields of the first year. The next most erratic behavior is for correlations involving yields of the year 1922.

The calculation of interannual correlations for the yields per tree of plots makes similar facts manifest. The coefficients obtained on a plot basis are of the same order as those obtained on an individual tree basis. As indicated in table 15, the values obtained for correlations of

TABLE 15

INTERANNUAL CORRELATION COEFFICIENTS FOR MEAN YIELD PER TREE OF PLOTS

	1922	1923	1924	1925	1926	1927
1921	+0.644±0.028	+0.168±0.047	−0.065±0.048	+0.114±0.048	−0.272±0.045	−0.002±0.048
1922		+0.173±0.047	+0.272±0.045	+0.486±0.037	+0.033±0.048	+0.014±0.048
1923			+0.597±0.031	+0.385±0.041	+0.402±0.041	+0.331±0.043
1924				+0.740±0.022	+0.688±0.026	+0.605±0.031
1925					+0.639±0.029	+0.554±0.034
1926						+0.606±0.031

the yield of plots in 1921 with the yield of similar plots in subsequent years are irregular. Similar correlations of plot yields in the year 1922 with those of following years are also variable, those for three years being positive, although small with the exception of the correlation with 1925, while with 1926 and 1927 the values are practically zero.

The correlations between plots involving all possible combinations of 1923 and later years are all positive and highly significant. In general, the values are highest for consecutive years and decrease slowly as the interval between the years increases. The ultimate limits of this tendency are, of course, a matter of conjecture. The actual magnitude of the correlations and their slow rate of decrease strongly suggest that a positive correlation may exist for a considerable period.

The agreement between the interannual correlations of yield of trees on one hand and those of plots or "plot averages" on the other, for the same periods, is additional evidence indicating that soil variability is the most important factor determining relative yields of plots. This appears to be reasonable in view of the high correlation existing between trees of the same plot in each year.

THE VALUE OF THE RECORDS OF YIELD IN VARIOUS INDIVIDUAL YEARS IN THE ANALYSIS OF THE PRODUCTION OF THE ORCHARD

It has been observed that the tendency for the relative yields of the trees and plots to approach the same value for the greater part of the period prior to the beginning of the experiment is not substantiated by the production of the trees in the year 1921. It seems that factors are operative which do not affect the subsequent yields. The frequency distribution of yields of individual trees also suggests that other factors, such as those concerned with the physiological condition of fruiting or nonfruiting, are operative. Many trees did not bear in 1921, and many more bore only a very small quantity of fruit.

The irregular relations of the yields of that year with the yields of other years suggest that production during the first year of bearing is not a reliable index of the performance of the trees in later periods. Had the field been under differential treatments, very different conclusions might easily have been inferred from the 1921 results than from those of following years. It seems, therefore, that the yields of these trees during the first year of production do not provide a reliable basis for the prediction of the responses of more mature trees. These records are not used, therefore, in calculations upon the reliability of various ways of laying out the field, treated in a later section of this paper.

Some question may possibly be raised, also, as to the reliability of the use of the yields of the second and the third years as indexes of productiveness of the trees. A considerable number of trees did not come into production until 1922. An additional factor which may have been of considerable importance in this respect was the effect of a freeze which occurred in January, 1922. The greatest amount of the damage occurred in the blocks west of the canal, where the fruit picked in 1922 was rendered unfit for sale. However, the weights of all the fruit were recorded soon after the freeze. Some damage to twigs was experienced, and this was also more severe west of the canal. Since the installation of orchard heaters in 1923, no further damage from this source has occurred.

Variability was greater in 1922 and 1923 than in following years. However, the graphs of the yields of those years (figs. 4, 5, and 6) indicate in most cases a tendency towards parallelism with the graphs of yields of later years, although there are striking exceptions, particularly for yields of 1922. The correlations between yields of trees in 1922 and yields in later years were positive and significant, though they were low in the more remote years. In two years the correlations between yields per tree of plots in 1922 and those in later years failed to be significant. The yields of trees and plots in 1923 were positively correlated with the yields in subsequent years. The curves which might be made from the yields of the trees in 1922 and 1923 would be nearly normal in type.

The factors which might cause exceptional responses in 1922 and 1923 may be of considerable importance in determining the reliability of the yields of these years. However, it has not been possible to separate the effect of "usual" seasonal influences on yield, which it is desirable to sample, from the effects of the physiological conditions accompanying the attainment of the fruiting condition and of the freeze in 1922. The influence of the changes accompanying fruiting are, however, not nearly so important in the later years as in 1921, judging by the frequency distributions. The nature of the interannual correlations suggests that the conditions affecting the responses of the trees in later years were also operative to an important extent during 1922 and 1923. Perhaps, therefore, it is safer to use the records for these two years, combined with the yields of the succeeding four years, as an index of productivity. No serious consequence would seem to result from this decision, although total variation may be slightly increased, and there is a possibility that correlations during the period for which the index is taken and the subsequent years may be reduced thereby.

There appears to be no objection to the use of yield records of the fourth to the seventh years as indicating, in part, the productivity of the trees during this preliminary period. The parallelism of the yield of groups of trees, the high interannual correlations existing, the nearly normal distributions noted, and the similarity of the coefficients of variation in the individual years all seem to indicate that in these years the responses of the trees and plots might well be obtained as samples of the same population. All are influenced chiefly by factors of a climatic nature and factors concerning the normal growth of the trees. These cause only limited fluctuations in the yield of individuals in various years.

THE VALUE OF THE AVERAGE YIELD OF SEVERAL YEARS

There is always involved in a group of field experiments the question of the accuracy of the trial during the period of its duration, and also the question of the probable results of a similar experiment over another series of years in the same location. Stadler[54] has emphasized the importance of the seasonal fluctuations in the responses of cereal crops, while Engledow and Yule[11] have clearly pointed out that the reliability of a prediction based upon the results of an experiment cannot be less than the error entailed by the sample of the seasons involved during the period of the experiment. In the case of orchard crops it is frequently very difficult, if not impossible, to maintain an experiment during a sufficient number of years to give a reliable sample of the seasons. Such a long period as would be necessary would involve other factors of possibly great importance owing to changes in age and size of the trees and to progressive or irreversible changes in the soil, so that it might be impossible to obtain an adequate sample of seasons for purposes of generalized prediction with one planting of trees. It is felt

TABLE 16

MEAN ANNUAL YIELD IN POUNDS PER TREE OF EACH PLOT* FROM 1922 TO 1927

Plot	Blocks									
	M	L	K	J	I	H	G	F	E	D
2	87	103	96	103	113				100	121
4	C-95	106	119	104	C-120				C-127	140
6	111	110	C-109	99	140				116	141
8	79	112	99	C-115	129				139	C-137
10	98	C-113	116	110	122				130	128
12	102	109	122	128	113				140	133
14	93	126	137	128	108	132			133	138
16	100	116	129	119	113	C-130			100	107
18	93	115	112	119	120	132			124	105
20	98	116	C-127	135	125	131			C-116	105
22	98	138	132	137	138	116	120		122	124
24	C-103	†	121	119	115	114	C-123		118	C-121
26	97	121	104	110	117	115	103			130
28	119	119	129	132	C-129	138	141			116
30	108	C-131	148	130	152	153	140			136
32	127	127	135	134	126	129	133	152		139
34	119	†	140	C-134	121	139	135	128		128
36	135	147	146	147	150	C-143	127	C-138		136
38	120	137	119	124	136	142	148	129		C-133
40	C-121	138	135	139	142	150	133	131		122
42	114	128	157	146	144	142	155	153		138
44	107	126	C-143	135	126	‡	C-144	165		144
46						126	155	155		146
48						C-129	140	140		C-117
50						134	142	131		115
52						114	150	C-149		122
54						114	136	†		108

Mean of entire field = 125.53

Mean of C plots = 125.88

* Locations of check, or continuity, plots are shown by the letter C. Plots related to each continuity plot by yield during the preliminary period are enclosed by horizontal lines.

† Plots omitted because of injury to trees.

‡ Omitted from present calculations because of injury.

that the use of a longer period for this study than the six years from 1922 to 1927 inclusive might possibly result in the introduction of complications such as those mentioned or those due to the effects of prolonged malnutrition of the trees. Thus the somewhat small size and pale color of the new leaves in 1927 suggested that the trees were beginning to suffer for lack of nutrients. Therefore, the treatments were started at that time.

In order to obtain an index of the productivity of the various plots during the period of six years, 1922–1927, the annual yields per tree for each plot have been averaged. This process, by smoothing some of the chance seasonal fluctuations, should result in a more reliable sample of the productive capacity of the individual plots during the preliminary period. The values obtained for the mean annual yield per tree for each plot are given in table 16. (The table gives certain other information which is discussed later.) The average probable error of the mean yields, calculated according to the method on page 103, is 3.29 per cent, or 4.34 pounds.

When the mean yields per tree of all plots were grouped into a frequency distribution with a class interval of 10 pounds, it was observed that the distribution resembled that of the normal curve. The critical functions β_1 and β_2, which serve as criteria of the curve type, were calculated according to the formulas given by Pearson[38] and by Elderton,[10] indicating:

$$\beta_1 = 0.048 \pm 0.034$$
$$\beta_2 = 2.729 \pm 0.176$$

Since β_1 is not significantly different from zero, and β_2 is not significantly different from 3.0 (the values of these functions for the normal, or Gaussian curve), it is evident that the distribution of the mean yields per tree of each plot for the six-year period is of normal, or practically normal, type. Therefore, the use of statistical methods involving an assumption of normality is justifiable with this material.

The following statistical constants for the mean yields per tree for all plots for the years 1922 to 1927 inclusive, are calculated by the use of a class interval of 10 pounds:

Number of plots	195
Mean yield	125.53 ± 0.787 pounds
Standard deviation	16.3 ± 0.56 pounds
Coefficient of variation	12.98 ± 0.45 per cent
Probable error of a single plot	10.99 pounds

The use of the six-year mean yield per tree for each plot results in a slight decrease in variation beyond that observed for individual years.

The failure of the variation to be reduced further by this procedure is due to the tendency of the plots to remain somewhat constant in relative yielding capacity during the period under consideration, as indicated in the previous discussion. This condition is emphasized further by use of the formula given on page 98 for the coefficient of variation of the mean of a combination of a group of related variates. The arithmetic mean of all the interannual correlations on a plot basis from 1922 to 1927 inclusive, is $+0.435$; the mean of the annual coefficients of variation on the same basis is 17.62 per cent. Substituting these values in the formula and solving, the coefficient of variation of the mean yield per tree for each plot is 12.82 per cent, which is very close to the observed value of 12.98 ± 0.45 per cent.

SOME RELATIONS OF THE VARIABILITY IN YIELD OF THE ORCHARD TO THE PLAN OF THE FUTURE EXPERIMENT

The results of studies of many blank, or uniformity, experiments suggest that knowledge of the normal variations in productivity of the field would be an advantage in planning the future experiment. In view of this, Love[31] and others have repeatedly emphasized the desirability of determining the characteristics of the variability of each field by means of the uniformity trial prior to the use of the field for comparative trials.

Batchelor and Reed[4] expressed the desirability of obtaining this information for orchard trees on which experiments are to be conducted. The importance of such study upon trees has since been emphasized by Anthony,[1] Chandler,[6, 7] and Gadd.[13] The data that have been presented strongly suggest that the plans which would give the most reliable results during this preliminary period might be expected also to give good results after the start of the differential treatments.

THE ERROR OF A SINGLE PLOT

It was noted that the probable error of a single observation of plot yields for this experiment over the six-year period, 1922–1927, is 10.99 pounds. This is 8.76 per cent of the mean annual tree yield.

From the value of the probable error of a single plot it is possible to determine the differences between any 2 plots which are theoretically necessary for any desired degree of assurance that the difference is real. Wood[69] has published convenient tables for this purpose, which were originally calculated from Sheppard's[51] distribution of the normal probability integral (see tables in Pearson,[38] or McEwen,[34] for extended work).[7] Wood's tables, which are presented again for convenient reference in Appendix A, give the ratio of the difference between any two means to the probable error of that difference for several levels of significance. The direction of the differences is determined in agricultural experiments by observation. In order to determine the odds that the difference is real the values in the lower half of Wood's table would be used.[8]

Since the probable error of a difference between the means of two sets of variables *which are not correlated* is given by the formula $E_{1\text{-}2} = \sqrt{E_1^2 + E_2^2}$ it is apparent that the probable error of a difference $(E_{1\text{-}2})$ between these means, when each has the same probable error, equals $E\sqrt{2}$. The values in the second vertical column of Wood's table give the ratios of the difference to such probable errors for the desired significance. For only a reasonable degree of assurance that conclusions as to the significance of an observed or hypothetical difference in an agricultural experiment are accurate, say 30 out of 31 times, the lower half of the table shows that the ratio of the difference (D) between two variables, each subject to the same probable error, to the error of that difference, $\frac{D}{E_{1\text{-}2}}$, must equal 3.81.

Applying this method of reasoning to the present situation, with the probable error of a single plot (E_s) noted above (10.99 pounds or 8.76 per cent), a difference of 3.81 $E_s = 41.87$ pounds per tree per plot (or 33.4 per cent of the mean tree yield) for six years would be necessary between any 2 plots to be certain 30 out of 31 times that a response to treatment in a given direction would be real.

Since it is often desirable to determine the effect of cultural treatments which are not expected to cause such great differences as those

[7] In the actual interpretation of the results of the future experiment by some of the methods which are to be discussed, the use of the normal distribution for the calculation of probabilities may not be warranted, owing to the small numbers of observations upon which the standard deviations may be based. Under such conditions Student's(57, 58) distribution of standard deviations of small samples should be used. Love,(29, 30) Love and Brunson,(32) Fisher,(12) McEwen,(34) Shewart,(52) and others have emphasized, extended, or facilitated the use of this distribution, while McEwen(34) and Conrad(9) have drawn attention to methods of comparing probabilities calculated from the two fundamental distributions. The theory of small samples has recently been summarized by Rider.(43) In the present study, however, the variability of the population is determined from a moderately large number of individuals, which may be considered to be normally distributed, as indicated above. Therefore, the calculation of the various statistical constants for individual observations and combinations of observations may be carried out according to the ordinary practices.

[8] This is the point of view assumed by Student(57) and by McEwen.(34) Of course, there are places where differences in either direction should be considered, and that part of Wood's table showing odds for them is included for reference.

noted above, it is apparent that the use of a single plot for each treatment is entirely unsatisfactory.

The difficulty obviously arises as a result of the failure of the yield of each plot to represent the yield of every other plot, or, in other words, to be a representative sample of the field as a whole. It is important that efforts be made to reduce the error of the individual treatment to smaller dimensions by securing a more nearly representative sample of the field for each treatment. Certain attempts to do this have been made.

THE EFFECT OF REPLICATION

It has been shown repeatedly that one of the most effective methods of reducing the error of the individual treatment is to increase the area devoted to it. The larger the area occupied by the sample used for each treatment, the more likely it is that its yield will represent that of the field as a whole. In a blank experiment, the hypothetical treatment area can be enlarged by increasing the number of unit plots assigned to each combination, or treatment, plot. The selection of the unit plots to be combined can be accomplished in many ways. It is possible, of course, to combine contiguous unit plots, but this has the effect of merely increasing the size of the single unit plot. It is also possible to select unit plots at random throughout the field and combine them into combination plots. With random choice of plots for this purpose an increase of the number of plots per combination should reduce the probable error of the combination plot (E_c) approximately in the relation $E_c = \frac{E_s}{\sqrt{n}}$ where n is the number of unit plots per combination, and E_s is the probable error of a single unit plot.

The effects of using various numbers of unit plots for each hypothetical treatment, with the replicates arranged in different ways, have been studied in the present experiment. Hypothetical combination plots, consisting of various numbers of unit plots, have been devised for each hypothetical treatment. In one set of comparisons the unit plots are contiguous, so that the entire area devoted to one combination plot is in one parcel.[9] In another set, the unit plots of the combination plot are systematically replicated, being separated by a number of units equal to the number of combination plots, less one. The coefficients of variation of combination plots of various sizes which have been formed in these ways are shown in table 17. In this table the theoretical coefficients

[9] In these arbitrary arrangements, plots were combined as follows: starting with plot D2 and continuing to D54, then from E2 to E24, from F32 to F54, etc., proceeding from north to south in each block, and from east to west between blocks. For ease of calculation each successive block is regarded as a continuation of the one before it. Plots which are not needed to make up complete combination plots at the south end of block M are disregarded.

which would be expected on the basis of random grouping of units of the combination plots are also given for comparison.

When contiguous plots are combined it is found that the variation of the combination plots is reduced as their size is increased, but that the reduction is not nearly so rapid as that expected theoretically on the basis of random replication. This is the result usually obtained by such grouping (Stevens and Vinall[(55)]). It is due to the fact that the yields of adjacent plots are positively correlated, in much the same way as are the yields of the trees in the same plots.

If, on the other hand, the area devoted to each treatment is increased by systematic replication of the unit plots, the variation of the combination plots is ordinarily reduced in somewhat the same degree as that expected by random replication (Stadler,[(54)] and Stevens and Vinall[(55)]). In the present case it is seen that the coefficients of variation of such combinations are, in the case of treatments of the same numbers of unit plots, slightly less than those anticipated according to the theory of probabilities.[10]

[10] It is desirable to know if the differences between col. *3* and cols. *4* and *5* of table 17 are significant. It has been pointed out to us by Professor G. F. McEwen, Scripps Institution of Oceanography, La Jolla, California, that, because of the approximate normality of the distribution from which the original standard deviation was derived, it is logical to determine the theoretical coefficient of variation for a small number of plots as in col. *3* of table 17, whereas the values in cols. *4* and *5* are subject to correction because of the small number of groups of plots (N) (col. *2*) from which these standard deviations are calculated. The value of the factor by which the standard deviation, or coefficient of variation, may be multiplied to give an approximation to the true values, is $\sqrt{\frac{N}{N-3}}$ for values of N greater than 30. For values of N equal to or less than 30, Dr. McEwen proposes the following method based on equating probabilities in Student's and the normal distribution.

Odds of 30 to 1 ($P=0.967$) are frequently regarded as the threshold of significance; therefore for any desired value of N the value of Z corresponding to this probability, as given in Student's table, is multiplied by $\sqrt{N}$ (since $Z=\frac{x}{\sigma_s}$) to obtain $Z\sqrt{N}=\frac{x}{\sigma_x}$ according to Student's distribution for small samples. The value of $\frac{x}{\sigma_x}$ corresponding to the same probability is then found in a table of the distribution of the normal probability integral. McEwen's (34) tables 13 and 14 are very convenient for this purpose. The ratio $\frac{Z\sqrt{N}}{\frac{x}{\sigma x}}$ is now the correction factor by which the measure of variability of the small population is multiplied. Applying these corrections to the coefficients of variation in the last two columns of table 17, and calculating the probable errors by the usual formula, the following values are obtained:

Number of plots (N)	Theoretical value $C\div\sqrt{N}$	Correction factor for cols. *4* and *5* of table 17	Corrected coefficient of variation: Contiguous plots combined	Corrected coefficient of variation: Systematically replicated plots combined
	per cent		*per cent*	*per cent*
195	12.98±0.45	—	12.98±0.45	12.98±0.45
97	9.18±0.45	1.016	11.34±0.56	8.01±0.39
48	6.49±0.45	1.033	10.13±0.70	5.82±0.40
32	5.30±0.45	1.050	9.49±0.81	3.85±0.32
24	4.59±0.45	1.072	7.91±0.77	4.19±0.41

From this tabulation it may be calculated that the *minimum* difference between the values of the theoretical coefficients and the coefficients of plots which are made up of contiguously combined units is 2.16 ±0.72 per cent, which may be considered barely significant. There is a real difference, therefore, in variation of combination plots made up in these different ways. On the other hand, the *maximum* difference to be found between any of the theoretical coefficients and the coefficients of systematically replicated plots for any given number of plots is 1.45±0.55, which is hardly considered significant. The variation of the systematically replicated plots, therefore, may be considered to approximate the theoretical.

The effect of the variability of the combination plots upon the difference theoretically necessary to give any desired degree of assurance that a real difference in yield would be caused by the treatments, can be calculated by the method discussed above. In order to obtain odds of 30 to 1 that the conclusions are sound, the probable error of a single

TABLE 17

EFFECT OF GROUPING VARIOUS NUMBERS OF UNIT PLOTS INTO COMBINATION PLOTS ACCORDING TO VARIOUS METHODS

Number of unit plots per combination (n)	Number of combinations possible (N)	Coefficient of variation (C) of combination plots, per cent		
		Theoretical= $C \div \sqrt{n}$	Contiguous plots combined	Systematically replicated plots combined
1	*2*	*3*	*4*	*5*
1	195	12.98	12.98	12.98
2	97	9.18	11.16	7.88
4	48	6.49	9.81	5.63
6	32	5.30	9.04	3.67
8	24	4.59	7.38	3.91

TABLE 18

THE DIFFERENCES NECESSARY BETWEEN THE MEANS OF COMBINATION PLOTS TO INSURE ODDS OF 30 TO 1 THAT THE DIFFERENCE IS DUE TO TREATMENT*

(In percentage of the mean yield of combination plots)

Number of plots per combination	Theoretical, with random sampling	Contiguous plots combined	Systematically replicated plots
1	*2*	*3*	*4*
1	33.36	33.36	33.36
2	23.59	28.68	20.25
4	16.68	25.21	14.47
6	13.62	23.23	9.43
8	11.80	18.97	10.05

* In these calculations 195 plots were used.

combination plot in percentage ($= \pm 0.6745\ C$, where C is the coefficient of variation, as given in table 17) should be multiplied by 3.81, if the direction is known or assumed. The results of this calculation are given in table 18.

The value of the use of systematically distributed unit plots for each treatment as compared to the use of the same number of contiguous unit plots is apparent from table 18. It may be seen that the minimum difference necessary between combination plots, formed from as many as 6 or 8 systematically distributed units, would need to be about 10 per cent of the mean annual tree yield, to insure odds of only 30 to 1 that a difference in one direction would be due to factors other than chance. As shown by columns *2* and *4* of table 18, these figures are approximately those which would be expected on the basis of the probability theory. The fact that the difference with 6 unit plots per treatment is less than with 8 plots indicates that certain distributions were by chance very favorable ones.

The magnitude of the difference necessary to give statistical precision to the comparisons between combination plots which are arranged in these ways, and the necessity of using large areas of land for each combination plot, point to the desirability of reducing the chance errors of the field by other methods if it is possible to do so.

THE USE OF CHECK PLOTS

Variability in the yield of plots of a uniformly treated experimental field is due to two types of factors. Factors of the first type are accidental, and may occur at random throughout the planting. They should be maintained at a minimum level by great care in conducting the experiment. Factors of the other type are commonly called systematic errors and tend to make all or a part of the plots yield alike. Thus climatic conditions may tend to depress the yields of all plots in certain years, or they may affect the plots in certain areas of the field more adversely or favorably than in other years. It has been shown above that the difficulties encountered in endeavoring to obtain a fair sample of the effects of the annual variations in climatic conditions on trees are very great. An element of judgment enters into the decision as to the length of time an experiment, and especially a preliminary experiment, should be continued. It was shown, however, that the use of the mean yield of six years in the present case reduced the variations somewhat, and that it seems to give a fairly reliable index of productivity.

Variations in the fertility of the soil of a single field are in general of a systematic nature also, and have long been known to be very important. Although exceptions occur occasionally in the case of single plots in an experiment, Harris[16] and several others have demonstrated that the mean correlation coefficient between yields of contiguous plots is nearly always positive and significant. The data presented above for the yield of combinations of contiguous plots showed that such a correlation exists between yields of adjacent plots in the orchard under discussion, and that important systematic variations are involved.

An attempt to reduce the errors due to this type of variation and thereby make the experiment more reliable has frequently led to the distribution of check plots throughout the experimental field. These plots serve (1) as the basis of comparison with nearby test plots, or (2) as a means of correcting the yields of the test plots, after which the corrected yields of the various plots may be compared among themselves by common statistical processes. The effectiveness of these two methods of employing check plots has been studied with the present data.

However, it is doubtful if the results of such a study of uniformly treated material prior to the start of an experiment should be applied without some qualification. To do so would be to assume that the yields of check and test plots would be correlated exactly to the same extent with different treatments as they are under conditions of uniform culture. Such may not always be the case. Stadler,[53] for instance, found that in variety trials with small grains, the nature of the variety used as the check was a factor in determining the efficiency of adjustment of test-plot yields. This is a phase of the problem of orchard trials upon which insufficient information is available. It is possible that certain treatments in such experiments might occasionally alter correlations between yields of nearby plots, and either increase or decrease systematic variations as compared with those observed under uniform conditions of culture. Although this possibility should be kept in mind during the following consideration of the effect of the use of check plots for comparison and for adjustment, conclusions based upon blank experiments should be correct in most cases.

Method of Calculating Adjusted Yield from Theoretical Check Yield.—The process of correcting the yields of test plots is termed adjustment of yields. Ordinarily, the first step in the process, as Stadler[53] has explained, is the calculation of the theoretical check yield of each test plot, which is the probable yield of each test plot, provided it had been given the same treatment as that of the check plots. Various methods of arriving at this value have been proposed, based upon assumptions which must be made as to the nature of changes in natural productivity from one part of the field to another between check plots. The use of the uniformity trial makes it possible to determine the probable value of these assumptions.

The next step in adjustment of the yields of test plots consists in calculating from the theoretical check yield the hypothetical or adjusted yield of the test plot, i.e., the approximate yield that would have been obtained provided the plot had been one of *average* fertility.

There are several ways of making this approximation. The theoretical check yield (T_{ch}) may be calculated by one of several methods which will be discussed. From this value, according to one method which seems to be useful for the present purpose, a factor, which Stadler[(53)] calls the "plot value" (P) may be determined by use of the formula:

$$P=\frac{T_{ch}}{M_{ch}},$$

where T_{ch} is the theoretical check yield, and M_{ch} the mean yield of the check plots. The adjusted yield is then obtained by:

$$Y_{adj}=\frac{Y_{act}}{P},$$

where Y_{adj} is the adjusted yield, Y_{act} is the actual yield of the test plots, and P the plot value. The two formulas may be combined for ease in calculation. When yields of check plots are adjusted by these formulas their variability is eliminated, for in that case $T_{ch} = Y_{act}$, and hence Y_{adj} becomes equal to M_{ch}. If the actual yields of the test plots should equal their theoretical check yields, the variability of the adjusted yields of the test plots would also be eliminated. The reduction of the variation of test plots, as measured by the coefficient of variation, becomes, therefore, the measure of the efficiency of adjustment by this process.[11]

[11] Certain statistical relations are suggested by the formulas noted above. In the formula

$$Y_{adj}=\frac{Y_{act}}{P}$$

the adjusted yield is a quotient, or index, and the usual statistical formulas for such ratios (Yule, [(70)] p. 214) hold true. Thus the mean of the adjusted yields

$$M_{adj}=\frac{M_{act}}{M_{pv}}\,(1-r\;V_{act}\;V_{pv}+V_{pv}^2).$$

In this formula, M_{adj} is the mean of the adjusted yields; M_{act}, the mean of the actual yields; M_{pv}, the mean of the plot values; r, the coefficient of correlation between either the plot values or the theoretical check yields and the actual yields of individual test plots; $V_{act}=\frac{\sigma}{M}$ of actual yields; and $V_{pv}=\frac{\sigma}{M}$ of either the plot values or theoretical check yields.

The coefficient of variation of the adjusted yields (C_{adj}) can be calculated from their mean (M_{adj}) and standard deviation $\left(C_{adj}=\frac{\sigma_{adj}\cdot 100}{M_{adj}}\right)$. Their standard deviation, σ_{adj}, is given by the formula (Yule, [(70)] p. 215) to which Stadler [(54)] has drawn attention:

$$\sigma_{adj}=\frac{M_{act}}{M_{pv}}\,(V^2_{act}-2r\;V_{act}\;V_{pv}+V_{pv}^2)^{\frac{1}{2}},$$

in which the symbols are the same as those given for the mean of the adjusted yields.

The coefficient of variation of the adjusted yields depends not alone on the correlation between the actual yields and either the calculated plot values or theoretical check yields, but also on the variability of actual and theoretical check yields. The correlation between actual yields and the calculated theoretical check yields of test plots is not, therefore, a precise index of the effectiveness of adjustment by means of check plots, although it has frequently been used for this purpose. This may be verified by observation of correlation coefficients calculated for the present data (table 19, col. *6*).

Effects of Various Methods of Calculating Theoretical Check Yield Upon Variation of Adjusted Yield.—The effects of certain methods of estimating the yields of theoretical check plots from distributed check plots, and the effect of adjustment of the yields of test plots upon their variability, have been studied for the uniformly treated orchard under consideration with check plots at various intervals.

For this purpose, the rectangular section of the field consisting of blocks I to M inclusive has been studied, since this area offers possibilities of arrangement not possessed by the field as a whole. The data for the mean annual yield per tree for each plot for the period 1922–1927 have been used for this study. It is probable that conclusions drawn from a study of this part of the orchard may be approximately true for the entire field, since the coefficient of variation for the entire field is 12.98 per cent, while that for blocks I to M inclusive, is 13.15 per cent. No prominent differences in the frequency distribution of yields are apparent.

Five arrangements of check plots have been tried on the 108 usable plots of the 5 blocks noted. The essential difference between the arrangements is in the frequency of the check plots. In each case the end plots of each block consist of check plots.[12]

Four methods of comparison have been tried with each arrangement of check plots. These are based upon the assumption that the value of the theoretical check yield of each test plot is equal to: (1) the mean of all check plots; (2) the nearest check;[13] (3) the interpolated value found by assuming a constant fertility gradient between 2 check plots; and (4) the mean of the check plot mean and the interpolated yield.[14]

[12] In two of the arrangements the number of test plots between check plots is not always constant, because the number of plots in the blocks is such that an extra plot is available with these two arrangements. In these two cases, therefore, the extra plot is arbitrarily inserted between the 2 check plots which are farthest south in each block, in order that the last plot may be a check plot.

The records of 2 plots in the field are not used, but the calculations are carried out in such a way that the interval is taken into account as if these 2 plots were used.

[13] When a test plot is located equidistant from 2 check plots their arithmetic mean is taken as the yield of the theoretical check.

[14] Various other formulas have been used by Stockberger,(56) Kiesselbach,(26) and others, which differ slightly from those given above in the assumptions involved in the calculation of the theoretical check yields. The above involve the basic assumptions of the majority of such formulas, however.

Methods of adjusting the yields of check plots before using them for adjustment of test plots have also been described. Thus Holtsmark and Larsen,(23) according to Roemer,(44) suggested that the mean of three nearby checks be obtained and used as a standard. McClelland(33) has also suggested that check plot values be smoothed by weighting them by a moving average method. It would seem that such operations occasionally might tend to produce lower correlations between theoretical check yields and actual yields of test plots if normal fluctuations in yields of contiguous test plots are rather sharp, and if checks were located at some distance. As abrupt changes in the yields of trees are frequently noted in the present experiment, in

Adjustment of the observed yields on the basis of these various calculations of the theoretical check yield was then made according to the method described in the text above.

The values for the coefficients of variation of the test plots before and after adjustment, according to the arrangement of each method, have

TABLE 19

EFFECT OF ADJUSTMENT BY USE OF CHECK PLOTS UPON VARIATION OF TEST PLOT YIELDS, BLOCKS I TO M

(Based on the mean annual yield per tree per plot, 1922–1927)

Frequency of checks	Method of calculating theoretical check yields	Coefficient of variation of test plots, in per cent		Reduction of variability, in per cent of unadjusted variability	Correlation coefficients between actual yield of test plots and their theoretical check yield or plot value
		Before adjustment	After adjustment		
1	*2*	*3*	*4*	*5*	*6*
No checks	....	13.15	....	....	....
3	*1.* Mean of checks..........	12.79	12.79	0.0	....
	2. Nearest check..........	12.79	10.40	18.7	+0.688±0.042
	3. 2/3 C_1+1/3 C_2..........	12.79	9.08	29.0	+0.715±0.040
	4. 1/2 (C_m+2/3 C_1+1/3 C_2)	12.79	9.46	26.0	+0.747±0.035
5 or 6	*1.* Mean of checks..........	13.26	13.26	0.0	....
	2. Nearest check..........	13.26	11.44	13.7	+0.599±0.048
	3. 4/5 C_1+1/5 C_2..........	13.26	9.53	28.1	+0.590±0.048
	4. 1/2 (C_m+4/5 C_1+1/5 C_2)	13.26	10.52	20.7	+0.599±0.048
7	*1.* Mean of checks..........	12.88	12.88	0.0	....
	2. Nearest check..........	12.88	11.59	10.0	+0.586±0.048
	3. 6/7 C_1+1/7 C_2..........	12.88	10.06	21.9	+0.641±0.042
	4. 1/2 (C_m+6/7 C_1+1/7 C_2)	12.88	9.51	26.2	+0.643±0.042
10 or 11	*1.* Mean of checks..........	12.85	12.85	0.0	....
	2. Nearest check..........	12.85	12.11	5.8	+0.620±0.043
	3. 9/10 C_1+1/10 C_2..........	12.85	10.54	18.0	+0.636±0.042
	4. 1/2(C_m+9/10C_1+1/10C_2)	12.85	9.82	23.6	+0.662±0.040
21	*1.* Mean of checks..........	12.87	12.87	0.0	....
	2. Nearest check..........	12.87	11.99	6.8	+0.612±0.043
	3. 20/21 C_1+1/21 C_2..........	12.87	8.38	34.9	+0.721±0.033
	4. 1/2 (C_m+20/21C_1+1/21C_2)	12.87	9.53	26.0	+0.693±0.035

been computed and are given in columns *3* and *4* of table 19. The percentage reduction in variation, based upon the coefficient of variation of the unadjusted yields, is given in column *5*.

It was found by inspection of the formulas for the plot values and for the adjusted yields that when the theoretical check yields of the test plots are assumed to be equal to the mean yield of the checks, no change in variation of the test plots occurs by adjustment with the method used.

common with many other uniformly treated orchards, the use of these methods in experiments with such material is probably of doubtful value as compared with the simpler formulas.

Although this method of comparison is frequently used in some form, it is apparent that adjustment based upon it must be differently applied, if it is to be helpful.

If the theoretical check yield of the test plot is taken as equal to the yield of the nearest check, and the actual yield of the test plot is adjusted accordingly, a slight to moderate reduction in variability is effected. This reduction occurs with checks at all the intervals tried, but it is greatest with the checks at close intervals.

The interpolation formulas (numbered *3* in tables 19 and 20) are based upon the assumption that the normal productivity between check plots varies uniformly. In the formulas $T_{ch} = \frac{2}{3} C_1 + \frac{1}{3} C_2$, etc., C_1 is the yield of the nearest check on one side of the test plot, and C_2 the yield of the nearest on the other side. Adjustment of the observed yields on the basis of the theoretical check yields obtained by this calculation results in values for the adjusted yields of the test plots which show considerably less variation than do the actual yields. The amount of reduction is greatest when the checks are close together and decreases as the interval between checks is increased, except at the greatest interval, with the checks only at each end of the field. Although the variation is reduced most with this extreme interval, indicating in this particular field a grading in productivity from one side to the other, certain very serious objections to locating the checks at this interval will shortly be noted.

If the theoretical check yield is assumed to be the mean of the check mean and the interpolated yield (formulas numbered *4* in tables 20 and 21), a reduction of the variation is also obtained by adjustment. In this case the amount of the reduction is about the same regardless of the interval between checks. However, it is apparent that the use of the check mean as a factor in calculating the theoretical check yields in formulas numbered *4* has not consistently changed the effect of adjustment as compared with that resulting from adjustment based upon the use of the interpolated yield alone as the theoretical check yield.

From the data of table 19 it appears that formulas involving the use of the interpolated yield, either alone or in conjunction with the mean of all the checks, in the calculation of the theoretical check yield give adjusted yields of less variation than any of the other methods tried.

Effects of Various Frequencies of Check Plots Upon Variation of Adjusted Yields.—In regard to the location of checks at various frequencies, if the case in which checks were located at every twenty-first plot is disregarded for the moment, it appears that the average reduction of variability of adjusted yields obtained by all methods is greatest when the checks are located at intervals of 3 plots. The average reduction becomes slightly less with checks at more remote intervals. This decrease in efficiency with various checks located at progressively greater distances is regularly reflected when the theoretical check yield is calculated on the basis of the nearest check (formulas numbered *2*), and on the basis of the interpolated yield between check plots (as in formulas numbered *3*). It is not apparent when the mean of the check mean plus the interpolated yield is used (formulas numbered *4*).

It was observed that the greatest reduction in variation was obtained by adjustment with the grading, or interpolation, method of calculation when checks were located at every twenty-first plot, indicating a gradual change in fertility from one side of the field to the other. In this case the check-plot rows were separated by a distance of 1,056 feet, and were located at the extreme northern and southern edges of the field. The value of such an arrangement may be seriously doubted. It may be a characteristic of this particular orchard due, by chance, to favorable yields of the limited number of check plots, which could not be reasonably expected to occur frequently. In addition it is conceivable that fluctuations might occur over a long period of years in plots distantly removed from the check, which will be independent of the treatment. The theoretical check yield would not reflect this change. A fundamental conception underlying the use of check plots, namely, that a correlation exists between the theoretical check yield and the actual yield (Richey,[40] and Stadler[54]), would be violated in such a case.

An additional hazard would result from the location of the check plots at the extremities of the field, or at extremely long intervals. This is the consequence resulting in case one check plot is rendered unfit by accident for comparison with the test plots. Such a situation is much more likely to occur with plots near the edge of the field, particularly if they are ever subject to wind damage or to increased difficulty of heating during cold weather. The location of check plots at these points, therefore, does not seem to be warranted in any trials upon this orchard in spite of the favorable coefficients of variation of the adjusted test plot yields obtained by their use.

Effects of Various Methods of Adjustment Upon Differences Necessary for Significance.—In order to be significant for comparison between plots, it is ordinarily considered that differences in yield should be great enough to insure odds of 30 to 1 that they are not due to chance variations. The several methods of calculating the theoretical check yields used resulted in reducing in varying degrees the differences between adjusted yields which are required for this significance, as is shown in columns *5* and *6* of table 20. The differences are expressed as percentages of mean adjusted yield of the test plots (this mean approaches the mean yield of check plots). These data were obtained by the procedure outlined in a preceding section of this paper. The minimum difference (in a given direction) between single unit plots found

TABLE 20

EFFECT OF ADJUSTMENT OF TEST-PLOT YIELDS BY USE OF CHECK PLOTS UPON DIFFERENCES NECESSARY FOR SIGNIFICANCE OF 30 TO 1 BETWEEN INDIVIDUAL TEST PLOTS AND BETWEEN THEORETICAL COMBINATION PLOTS*

Frequency of checks	Number of unit test plots available	Theoretical number of unit plots for each of 15 combinations	Method of calculating theoretical check yield	Necessary differences in one direction, in per cent of mean adjusted yield of test plots		
				Between single plots		Between combination plots after adjustment
				Before adjustment	After adjustment	
1	*2*	*3*	*4*	*5*	*6*	*7*
No checks	108	7.20	....	33.79	....	12.59
3	68	4.53	*1.* Mean of checks	32.87	32.87	15.44
			2. Nearest check	32.87	26.73	12.56
			3. 2/3 C_1+1/3 C_2	32.87	23.33	10.96
			4. 1/2 (C_m+2/3 C_1+1/3 C_2)	32.87	24.31	11.42
5 or 6	83	5.53	*1.* Mean of checks	34.08	34.08	14.49
			2. Nearest check	34.08	29.40	12.50
			3. 4/5 C_1+1/5 C_2	34.08	24.49	10.41
			4. 1/2 (C_m+4/5 C_1+1/5 C_2)	34.08	27.03	11.49
7	88	5.87	*1.* Mean of checks	33.10	33.10	13.66
			2. Nearest check	33.10	29.78	12.29
			3. 6/7 C_1+1/7 C_2	33.10	25.85	10.67
			4. 1/2 (C_m+6/7 C_1+1/7 C_2)	33.10	24.44	10.09
10 or 11	93	6.20	*1.* Mean of checks	33.02	33.02	13.26
			2. Nearest check	33.02	31.12	12.50
			3. 9/10 C_1+1/10 C_2	33.02	27.09	10.88
			4. 1/2 (C_m+9/10 C_1+1/10 C_2)	33.02	25.24	10.14
21	98	6.53	*1.* Mean of checks	33.07	33.07	12.94
			2. Nearest check	33.07	30.81	12.06
			3. 20/21 C_1+1/21 C_2	33.07	21.54	8.43
			4. 1/2 (C_m+20/21 C_1+1/21 C_2)	33.07	24.49	9.58

*Calculated from data of table 19.

necessary for significance is 23.33 per cent of the mean with checks at all frequencies, except at every twenty-first plot. This is a considerable reduction from the differences necessary between unadjusted yields of unit plots, which were found to be about 33 per cent.

Further decreases in the differences necessary between treatments could be obtained by increasing the area devoted to each treatment. If this were done by random replication of the unit plots for each combination, or treatment, plot, it is probable that the coefficient of variation of the treatment, and hence the differences necessary for any degree of significance between treatments, would be decreased approximately according to the formula:

$$C_c = \frac{C_u}{\sqrt{n}},$$

where C_c is the coefficient of variation of the combination plots, C_u is the coefficient of variation of the unit plots, and n is the number of unit plots in each treatment. This increase in number of plots per treatment would result in increased reliability in this case, in the same way that it was shown to have an effect in the above discussion of the probable error of a single plot, and would be very effective in reducing the differences between combination plots necessary for significance.

The use of systematically replicated check plots as a basis for adjustment of test-plot yields in an experiment upon this orchard would apparently result in a reduction of the errors involved in trials upon it. However, such a decrease would be obtained only by the allocation of a large number of plots for use as check plots which might otherwise be used as additional replicates of the test plots. The possibility of securing greater reliability by the use of check plots as described, than by increasing the area of each treatment by the use of the possible check plots for additional replications of combination plots may be determined in a theoretical manner.

If 15 treatments are to be tried upon the plots of blocks I to M inclusive, it is possible to determine the probable error of each combination plot, based upon the variation of the adjusted yields where check plots are used, and upon the variation of all of the plots for the unadjusted yields. The total number of test plots available with each arrangement of check plots varies, of course, and the theoretical (since fractions are involved) number of these which may be used for each of the 15 treatments is given in columns *2* and *3* of table 20. Since, in a case of random assortment, the coefficients of variation of unit plots bear the relation noted above to the coefficient of variation of combination plots, it is possible from these data to calculate the probable error of a single combination plot, and, hence, the difference between combinations or treatments necessary for significance. The values necessary to assure odds of 30 to 1 are set forth in column *7*, for assumed differences in one direction. If the arrangement of checks at each side of the orchard (every twenty-first plot) is disregarded, the adjustment of yields by check plots does not reduce the difference necessary for significance of this degree by more than 2.5 per cent of the mean yield (from 12.59 to 10.09 per cent), a reduction in percentage of 19.86 per cent, based upon the unadjusted yields where no checks are used.

Judged by this method of analysis, the interpolation formula, *3*, is very slightly more efficient than the combination formula, *4*, with check plots at intervals of 3, and 5 or 6 plots. With checks at intervals of 7, and 10 or 11 plots the combination formula shows a very slight advantage over the interpolation formula. The calculation of the theoretical check yield by either of these formulas is apparently more reliable in this comparison than according to the assumption that the theoretical check yield of each test plot is equal to that of the nearest check. Although the illustration is hypothetical, since the number of unit plots per treatment has been expressed in fractions, it indicates that adjustment of yields by means of checks would probably reduce the errors of trials upon this orchard more than would the increased replication of test plots that would be made possible by elimination of the check plots. Although the increase (nearly 20 per cent) in reliability seems important, the minimum differences between combinations which would be necessary for only moderate significance (10.09 per cent of the mean adjusted yield), are still greater than some of the treatments may cause. It is desirable to see if even better methods of comparison may be obtained with the use of check plots.

The Comparison of Single Treatments With a Check Treatment.— The elimination of systematic errors in various parts of the experimental field has been attempted frequently by the comparison of the various treatments with a standard treatment which is used for the check plots. In such cases the treatment of the check plots is ordinarily one which is known to give good results, and which it is desirable to surpass. The method involves, fundamentally, the calculation of the difference between the mean yield of each treatment and the mean of its theoretical check yields, which is then compared with the probable error of the difference as a test of significance. The probable error of a series of differences can be determined directly, or, if certain statistics are known, from the full formula for the variance (squared standard deviation) of a difference. The latter formula, as frequently emphasized (Student,[59, 60] Kemp,[25] Richey,[40] Sax,[47] etc.) is:

$$\sigma^2_{1-2} = \sigma^2_1 + \sigma^2_2 - 2r_{1.2}\,\sigma_1\,\sigma_2$$

The last term in the equation can be eliminated only in case both populations are sampled at random, when $r = 0$. This is obviously not the case in the present situation, for the theoretical and actual yields of the test plots are correlated.

Another method for obtaining the differences necessary for comparing a single treatment with the check treatment leads to the same results as the methods just given, and the calculations may sometimes be more conveniently made. This involves the determination of the differences between the mean of the check plots and the adjusted yields of the test plots devoted to the particular treatment, when adjustments are made according to the method previously discussed. The calculation of the variance of the differences, as determined by means of the complete formula given above, is very simple in this case, for the variance of the mean of the checks is zero, and there is no correlation between the mean of the checks and the adjusted yields. Hence (Stadler[54]), the variance of the difference equals the variance of the adjusted yields.

The relations of these two methods may be illustrated by the case given above, with a check every third plot when the calculation of the theoretical check yield is carried out according to the formula $\frac{2}{3} C_1 + \frac{1}{3} C_2$. The following values have been determined:

σ_1, the standard deviation of theoretical check yield $= 13.2$
σ_2, the standard deviation of actual yields $= 15.74$

When these values are substituted in the full formula for the standard deviation of a difference, we find:

$$\sigma_{1-2} = 11.18$$

This value, when divided by 123.25 (the mean of the adjusted yields) and multiplied by 100 to place it on a comparable basis, becomes 9.07 per cent, which is very close to the value given in table 19 for the coefficient of variation of the adjusted yields of the test plots (9.08 per cent). The choice of method depends solely on convenience.

The use of the value 9.07 per cent as the coefficient of variation of a difference, makes it possible to calculate the difference in yield necessary for significance between any 2 theoretical check and test plots. In this case column *1* in the table of odds given in Appendix A should be used since the difference is compared with its own probable error. In order to obtain odds of 30 to 1 that conclusions as to the significance of a given difference (D) are correct, then,

$$\frac{D}{0.6745 \cdot 9.07} = 2.70;\ D = 16.52 \text{ per cent.}$$

By comparison with comparable data from table 20, the differences necessary for significance between single plots may thus be seen to be considerably less when comparisons are drawn between individual theoretical check plots and test plots, than when they are drawn between different individual adjusted test plots (23.33 per cent). This is in agreement with Stadler's discussion.[54] The replication of such plots should reduce the errors by approximately $\frac{1}{\sqrt{n}}$, where n is the number of test plots per combination plot.

The use of methods of differences between test and check plots, however, does not appear to be an advantage when extended to a comparison of 2 test plots or 2 combination plots (test plots receiving the same treatment). In order to compare the mean differences and their probable errors, which have been determined for each of the combination plots in comparison with their check plots, the formula for the probable error of a difference between two means must be used. In that case the use of methods of differences between combination and check plots gives the same results as the direct comparison of adjusted yields of the test plots.

THE COMPARISON OF NEARBY TEST PLOTS BY METHODS OF DIFFERENCES

It has been indicated above that in the full formula for the variance of a difference, $\sigma^2_{1\text{-}2} = \sigma^2_1 + \sigma^2_2 - 2r_{1\cdot 2}\ \sigma_1\ \sigma_2$, the last term can be eliminated only when the correlation between the observations is zero. In field trials this is seldom the case, for there is usually a tendency towards concomitant variation of nearby test plots between which comparisons are drawn. Therefore, it is possible to reduce the error of the mean difference between 2 treatments, as usually determined, by the calculation of the correlation between nearby test plots of the 2 treatments and the utilization of the last term in the equation. Love[29] has pointed out that the same effect can be secured by obtaining the mean of the differences between individual correlated test plots which are being compared, and directly calculating the variance of that mean.

This procedure has the effect of reducing the errors due to systematic variation, which is the cause of the correlations. The amount of the reduction will depend upon the size of the correlation. This consideration has led Student,[59] p. 273, to remark that "the art of designing all experiments lies even more in arranging matters so that $r_{1\text{-}2}$ is as large as possible, than in reducing σ^2_1 and σ^2_2."

It is anticipated that the results obtained on the present field by the application of the method of comparing the unadjusted yields of test plots which are replicated at random would, on the whole, be somewhat less reliable than those obtained by the use of check plots for adjustment. Because of the large number of treatments which are proposed for trial the plots to be compared in the same replication series would be located, on the average, at some distance from each other. In some cases they would be at opposite sides of the field in different blocks.

Consequently, the correlation between "paired" test plots would be small.

The calculation of the errors of all possible differences between treatments is very laborious. Fortunately, Student[59] and R. A. Fisher have developed a method by which the mean error of the differences of all the possible comparisons can be obtained. This method may be used to illustrate the effect of the procedure upon the material under consideration. By their formula, the variance of a mean difference between any 2 sets of m treatments, each tried n times, is:

$$\sigma^2_{\bar{d}} = \frac{2m(\sigma^2_T - \sigma^2_R - \sigma^2_G)}{(m-1)(n-1)},$$

when σ^2_T is the total variance of the plots; σ^2_R, the variance of the treatment means; and σ^2_G, the variance of the replication series means. The formula is discussed in some detail by Student,[59] and in a slightly modified form by Engledow and Yule.[11]

The application of the formula to the data at hand can be made by assuming that any likely number of plots be devoted to each treatment on the 108 plots in blocks I to M inclusive. If 4 plots are used for each theoretical treatment, 27 treatments are possible on this area. If the treatments in each replication series are in the same order, starting at I–2 and progressing to I–44, then to J–2, etc., repeating until the 27 treatments have been allocated to 4 plots each, the calculation of the formula indicates that the variance of the mean difference, $\sigma^2_{\bar{d}}$, between the means of the treatment yields is 132.26, and the standard deviation of the mean difference, $\sigma_{\bar{d}}$, is, hence, 11.50 pounds; this is 9.48 per cent of the mean yield of the 108 plots. If this percentage be multiplied by 0.6745 to obtain the probable error in per cent and by 2.7 (the ratio of the mean to its probable error necessary to give 30 to 1 odds), the difference between treatment means necessary to give this significance is found to be 17.26 per cent. This difference is not far from those which were indicated in table 18 as theoretically necessary between the means of groups of 4 test plots systematically replicated throughout the entire field. Although somewhat better arrangements than the one noted might be obtained by chance, it seems probable that, with many treatments and few replications on this planting, the desired high correlation between the plots in each replication series would be lacking. Consequently, with chance or systematic arrangement of plots, the comparison of nearby test plots by methods of differences would not appreciably eliminate the effects of systematic soil variations nor reduce the errors of experiments upon the planting.

ADJUSTMENT OF YIELDS OF TEST PLOTS BY MEANS OF CONTIGUOUS TEST PLOTS

Various investigators have attempted the elimination of systematic variations in different parts of the experimental field by the use of the yields of neighboring test plots as the standard for the adjustment of the individual plots. The methods of Hummel,[24] Mitscherlich,[35] Surface and Pearl,[61] and Richey[40, 41, 42] are perhaps best known. Their general advantages have been discussed by Stadler,[54] and consist in the release of check plots for increased replication of test plots, the avoidance of the possibly unfair effect of adjustment of certain treatments by means of a single check treatment, the avoidance of undue effect of great chance fluctuations in the yield of a particular plot which may be used as a check, and the determination of the theoretical check yield of the test plot by means of contiguous plots rather than by remote plots.

The objections to such methods of adjustment in the usual type of cultural trials with fruit trees lie, however, in the probability that large numbers of treatments must be tried in a single experimental field, and that the number of replications will be narrowly limited. In this case a fundamental conception upon which certain of the above methods are based, may be violated, namely, that the mean yield of each set of replicated test plots designated as a combination plot is a "fair index of its productiveness" (Richey[40] p. 90). Furthermore, unless the number of replications of each treatment equals or exceeds the number of treatments in the experiment, the use of these methods assumes (Richey[40, 41]) that the influence of particular treatments upon the theoretical check yields of plots contiguous to them will not be so great as to introduce serious errors. In orchard trials of long duration, the range of the responses caused by cultural treatments may be extremely wide, so that the effects of adjustment by plots differing widely in yield, might unduly favor or handicap individual plots.

These considerations make it evident that if a trial which involves many widely differing treatments with relatively few replications for each is anticipated, the study of the effect of adjustment of yields of test plots by one another while under conditions of uniform culture prior to the start of the experiment proper, may occasionally lead to expectations which will not be justified after the experiment goes into operation. Fortunately the requirements of such methods as to the plan of the experiment in addition to those given above are not stringent, being only that the treatments should not appear in the same order in the different replication series. As a consequence the methods may often be applied and their benefits realized whether check plots are employed or not.

It is apparent that in the plan of the experimental orchard under discussion it would be unwise to place the entire responsibility for the reduction of the experimental errors and for the interpretation of the results to be obtained upon such methods of adjustment of yields. It would seem safer to find the alternative plans which appear to be most reliable for the conditions of the experiment. The application of methods of adjustment of yield data by means of contiguous test plots may still be made when the experiment is in operation, and used in the interpretation of the effect of the treatments, if they seem to lead to more reliable conclusions than other methods.

ADJUSTMENT OF YIELDS ON THE BASIS OF PAST PERFORMANCE

It has been observed in a previous section that in general a significantly positive correlation exists in successive years between the yields of plots planted to annual crops. It is conceivable, therefore, that the yields of the plots obtained under conditions of uniform culture might be used to establish indexes which will approximate the relative productive capacity of the plots. These indexes might then be used for adjustment of yields to reduce the effects of systematic soil variations, or as a basis for locating the plots for each treatment in the experiment.

Such a study involving both possibilities was made many years ago by Wagner.[62] He concluded that the relative yields of plots in two consecutive years are not sufficiently alike for their use to be of value. Other workers (Roemer[44]) with field crops have come to the same conclusion. However, their studies have been made upon the yields of single or of few years, rather than yields of a large number of years. As Lehmann,[27] Harris and Scofield,[18, 19] and others have shown, weather conditions exert a great influence on relative yields of plots planted to annual crops, and it is possible that other results might ensue if representative samples of the climatic effects could be obtained in studies of these methods. It also seems possible that methods of analysis may be used which will take advantage of interannual correlations to reduce variability, even though the correlations may be small.

There are certain factors inherent in experimental work with trees which strongly suggest that the use of past records in formulating the plan of an experiment may be of more value than is the case with annual crops. The condition of each tree at the beginning of an experiment is the result of its parentage and environment, by which the size, nature of development, and state of vigor of the plants at the beginning of the experiment are established, and to some extent influenced during the experiment. These characteristics are reflected in their yields. It is conceivable, therefore, that significantly positive interannual correlations may be found more consistently in the case of yields of trees than with annual crops where, in experimental field work, individual plant variations are ordinarily eliminated and the response of the plots depends only on the conditions of soil and climate prevailing in the particular crop year.

Attention has already been called in the present paper to the fact that the yields of fruit trees and plots of trees in individual plantings have frequently exhibited a tendency to have about the same gross variation in different years. This seems to imply a correlation in yields of trees in different years. Such correlations have, in fact, been observed by several writers.

The practical use of these tendencies of trees and of plots of particular plantings to maintain their variability and relative productivity over a term of years in the technique of orchard experimentation has been advanced by numerous investigators. Batchelor and Reed[(4)] discussed the suggestion that a knowledge of the variation of the trees of a planting, obtained under conditions of uniform culture, be used to estimate the errors of the future experiment. The suggested use of yield data secured prior to the beginning of the experiment has been carried further by Chandler[(6, 7)] who discussed the suggestion that the orchard be maintained under uniform care for a period of two to four years. Plots could then be so arranged that the average yield for each plot during this preliminary period would be nearly the same[(6)] p. 238,[15] "or else the yield of each plot during this preliminary period could be

[15] This procedure is similar to the technique of Wagner,[(62)] who selected for comparison plots which deviated equally from the mean yield in one year under conditions of uniform treatment. The following year Wagner compared the deviations of these paired plots under the same cultural conditions and found them unequal. Wagner also suggested that the deviations observed in a preliminary trial could be used for correcting the yields in the experiment which followed.

The method of combining plots so that the preliminary yields for each treatment were equal was followed by Lehmann.[(27)] This investigator kept a record of the yield of 105 untreated plots of Ragi or African millet, *Eleusine coràcana*, from 1905 to 1907. At the end of this period he discarded the yields of 1906 because of extreme weather conditions, and established the relative yield of the plots in percentage of the mean, a process which he called "standardization." He discarded the plots which showed results widely divergent from the mean yield in 1905 and 1907 and averaged the yields of each of the remaining plots for these two years. These plots were than grouped, 2 plots to a treatment, in such a way that the mean yields of the combination plots were equal to the mean of the field for the preliminary period. No published results of the experiment as planned by Lehmann have been found. His experiment was carried on for a period of five years from 1908 by L. C. Coleman and then abandoned, since it was thought that "this sort of experimental procedure would not lead to accurate results. .... The reason for this lay..... in the fact that duplicate plots lay widely scattered on land lying on a fairly steep slope, so that soil moisture conditions were likely to vary widely. These depend upon a rainfall distribution that varies so from year to year that it would take probably ten or fifteen years to get a fair average." (Correspondence of L. C. Coleman dated May 31, 1929.)

used in weighting the results obtained from the plots receiving the different treatments."[7] p. 8.

The above suggestions concerning the application of preliminary yield records in the plan of the experiment seem to involve two fundamental concepts: (1) that by selecting replicates for all individual treatments so that the total preliminary yield may be about equal for each treatment, a more representative sample of the field may be obtained with the same number of replicated plots; (2) that the relative yield of each plot obtained under conditions of uniform culture, if expressed as a decimal fraction of the mean yield of the field, may be used as a plot value to adjust actual yields and to reduce variation in the experiment which follows. If the plot value remained constant during both the preliminary and actual trials adjustment based on plot values obtained in the period of preliminary testing would eliminate variation during the period of differential treatments. However, since the interannual correlations in yield have in no case been reported as equal to + 1.0, the plot values cannot be expected to remain constant. There is an error attached to their use which should be taken into consideration. The ordinary methods of standardization neglect this error.

However, another method of using preliminary yields to reduce the errors of an experiment may be employed. This method is based upon the calculation of the significance of the differences between correlated replicates of 2 treatments. The variance of the difference is decreased as the correlation between paired plots increases. In ordinary practice the contiguous plots are regarded as being in the same replication series for purposes of comparison, since there is frequently a positive correlation between nearby plots, as Harris,[16, 17] has demonstrated. It has been demonstrated heretofore, however, that when this method is applied to these data, using few replications which are widely separated, there is, on the average, no increase in reliability. This, it has been shown, means that there is little average correlation between the plots of the same replication series under such conditions. If, however, the plots of 2 treatments could be chosen for comparison on any other basis so that their yields would be correlated, the method of differences could be used to advantage. It seems probable that the relative yields of plots obtained prior to the beginning of an experiment could be used for this purpose. Richey,[41] p. 1163, in a discussion of this subject as applied to a hypothetical example with fruit trees, states: "if ..... data obtained on the yields of the same plats under uniform treatment prior to beginning the experiment had shown the inherent productive capacity of the plats to be in this (or any other) order, it would be very desirable to pair the plats as indicated by the preliminary data.''[16] Recently Hoffman [(22)] has reported the plan of a fertilizer experiment with raspberries, based upon this principle. He selected plots for each treatment in such a way that the paired replicates were from the same yield group, as determined by the yields of the plants during the year 1929 under conditions of uniform culture.

The special advantages of such an arrangement would seem to persist as long as the yields of the plots, after the differential treatments have gone into effect, are correlated with the yields during the prior period of uniform care. As long as this correlation persists there would be some correlation on the average between the individual plots in each yield group.

A scheme in orchard experimentation which is fundamentally very similar was followed in 1924 by Anthony.[(2)] Waring[(63)] had previously reported that in several experimental apple orchards the yield of trees was correlated with the circumference of the trunk of the tree. Anthony[(2)] therefore, selected individual paired trees in a twenty-year-old orchard for different treatments on the basis of their equality in trunk circumference. He then planned to compare these paired trees by a method of differences. Since girth at the time the experiment is started is the result of growth preceding that time, and Waring had shown that girth is correlated with yield, the method is similar to that involving the pairing of plots on the basis of past yields.

If the preliminary yields of trees and plots of trees are correlated with their yields during an experiment, an advantage additional to those mentioned can be secured by arranging the plots on the basis of their preliminary yields. This is the possibility of obtaining for each treatment, samples of the trees (and plots) which are fairly representative of the variability of the experimental material. By this is meant the opportunity of selecting plots supporting trees in different conditions for each treatment. It is possible that some treatments might affect trees in all conditions of vigor which prevail in the plantings, while others may be effective only on trees relatively low in vigor. Such relations would be of great interest. In case a treatment does affect plots of the several yield groups differently, the correlation of the yields before and after treatment would probably be changed by that par-

[16] A method of arrangement of the experimental orchard under consideration, in such a way that the mean preliminary yields of all treatments would be equal, and in which the plots of each treatment were arranged in the order of productiveness so as to permit the use of Student's[(59)] method for the determination of the mean variance of the difference between treatments was suggested by Mr. Richey in correspondence with the authors dated May 28, 1925.

ticular treatment from the relation that would have prevailed had the original cultural conditions been maintained. It is difficult to tell beforehand, however, whether alterations in this correlation would greatly change the differences necessary for significance in the actual trial. The coefficient of variation of the combination plots would also be altered and very possibly in the same direction as the change in the correlation coefficient. In any event the inclusion of the same number of comparable trees in each combination plot would seem desirable from a horticultural, as well as from a statistical point of view.

PLAN OF THE EXPERIMENTAL ORCHARD

The present experiment with Washington Navel orange trees has been planned in an attempt to make use of any benefit which may accrue through study of the yields prior to the beginning of the differential treatments. This plan was placed in operation during the spring of 1927.

Sole dependence, however, upon methods of interpretation of the future experiment based upon standardization processes, would, with our present knowledge, involve certain dangers which have not been disregarded. Chief of these, even if the climate be adequately sampled, is that the correlation of yields before and after the beginning of the treatments may not be high enough for direct adjustment to be effective. This might be due to increasing age of the trees, which might influence their reaction to a given set of conditions. A likely source of disturbance, also, is the possibility that soil changes, either natural or because of treatment, may be progressive and that their effects may be cumulative either in the soil or in the trees. Under such conditions yields of the trees would reflect the changed conditions. It is felt, therefore, although the preliminary data may be valuable in the present case, that precautions should be taken to make possible the use of other methods of analysis than those based upon it.

NUMBER OF REPLICATIONS

It was pointed out above that increasing the number of plots devoted to each treatment increases the likelihood that a representative sample of the field will be obtained for each treatment. When the replicates were systematically distributed in blocks I to M inclusive, the reduction in variability obtained by replication was approximately that expected on the basis of random sampling. Although it would be desirable to have a large number of replicates for each treatment it is nearly always necessary to limit the number. Since the number of treatments which it is necessary to try in the present experiment is large, the number of replicates for each treatment must be small. The most practical use of the area for the present purpose appears to result when 4 plots are used for each treatment. This number of plots was found to be satisfactory by Batchelor and Reed[4] in their study of orchard uniformity trials. It has also been found of satisfactory reliability by Livermore[28] for potato trials with single-row plots 36 feet long, the variability of which is comparable to that of plots in orchard trials.

This limitation of the number of replications lessens the accuracy of interpretation of the experiment. However, it is believed that the loss in accuracy due to this factor will be compensated by the cumulative effect of the treatments. There is also the possibility of interpreting the future experiment by means of pairing plots in this experiment. This possibility is enhanced by the fact that the specific treatments have been planned in such a way that in many cases a larger number than 4 plots may be compared. These possibilities, however, depend on the nature of the treatments and cannot enter into the present discussion.

The reliability of comparison between any 2 treatments, each repeated 4 times on plots which are not correlated in yield, can be approximately determined. If the coefficient of variation of the plots is the same during the period of differential treatments as before their initiation (see p. 114), average differences of approximately 16.7 per cent would be necessary between 2 treatments. If the variation can be reduced by any method, however, the differences necessary for significance will be decreased proportionately.

THE ALLOCATION OF CHECK PLOTS

Although the use of check plots involves some assumptions, it has certain advantages which safeguard an experiment that may be of long duration. Adjustment of the yields of test plots by check plots is done without introduction of *a priori* knowledge. Studies of preliminary yields have indicated that increased reliability would be obtained by adjustment based upon check plot yields in the planting under consideration. Check plots are ordinarily located at intervals which are close enough to render comparisons between the check treatment and each individual treatment rather more accurate than comparisons between any other 2 treatments. Check plots should be frequent enough to give a reliable sample of the field as a whole, and thus permit the determination of average variation, and of the effects of climatic influence and the time factor upon the variations of soil and trees.

It is thought that the possible advantages of check plots should not be overlooked in the plan of this experimental orchard. Under conditions of uniform treatment prior to the beginning of the experiment, adjustment by check plots renders significant differences of about 12 per cent in one direction between any 2 combinations of 4 plots each (table 20, values of column *6* divided by $\sqrt{4}$). Differences as low as about 8.3 per cent in one direction might be significant in comparisons of any particular individual treatment of 4 plots each with the check treatment (value for D on page 125 divided by $\sqrt{4}$). These decreases in differences necessary for significance justify the use of check plots. Provision has therefore been made for them in the future experiment.

However, the necessity of trying many treatments in the experiment requires that the number of check plots be kept as small as possible. In the above study of the effect of adjustment by means of systematically replicated checks, it was indicated that the more frequent the check plots the greater was the reduction in variation of test plots after adjustment, with the exception of the inadvisable case where the checks were located on each side of the field. The gain in precision is slight, however, as the number of check plots is increased. It seems that the release of as many plots as possible for use as test plots would outweigh the slight gain in reliability to be obtained by having checks at the more usual intervals of 3 to 5 plots. It has been decided, therefore, to use 25 check plots in the field of 199 plots. The area which they occupy is 12.6 per cent of the whole planting.

The location of these 25 check plots has been determined arbitrarily on the basis of their yields during the preliminary period of uniform culture. This has been done in such a way that they are a fair sample for the preliminary period of the yield of the field as a whole, and also of the local areas in which each plot is situated. It is planned that these plots shall be used to measure the continuity of relative differences between various sections of the field before and after the initiation of the treatments. For this reason, but chiefly to avoid confusion with the usual use of check plots, they have been called "continuity" plots.

Inspection of the data of the mean annual yield per tree of each plot for the six-year period (table 16), shows that there is frequently a tendency for groups of plots to yield approximately alike.[17] Consequently, these plots were grouped together as nearly as was practicable, with regard for numbers of plots in each group and for the location of the groups as a whole in relation to each other. The mean yield of each

[17] The more productive areas were correlated with the presence of slightly more luxuriant leaves in the early spring of 1927.

group of plots was determined. One plot in each group, the yield of which was as close as possible to the mean yield of the group, was then selected as the continuity plot. Occasional compromises were made in order to secure a more satisfactory geographical scattering of the continuity plots. The location of the plots selected is indicated in table 16.

TABLE 21

PRELIMINARY YIELD OF CONTINUITY PLOTS AND MEAN YIELD OF PLOTS IN AREA ADJACENT TO EACH

(Mean annual yields per tree for 1922–1927)

Continuity plots		Adjacent plots		
Location	Yield	Number of plots*	Location	Mean yield
	pounds			*pounds*
D8	137	6	D2 - D14	134
D24	121	6	D16 - D28	115
D38	133	8	D30 - D46	136
D48	117	3	D48 - D54	115
E4	127	6	E2 - E14	126
E20	116	4	E16 - E24	116
F36	138	5	F32 - F42	139
F52	149	4	F44 - F54	148
G24	123	7	G22 - G36	128
G44	144	8	G38 - G54	146
H16	130	6	H14 - H26	123
H36	143	6	H28 - H40	142
H48	129	5	H42 - H54	126
I4	120	6	I2 - I14	121
I28	129	14	I16 - I44	130
J8	115	10	J2 - J22.	118
J34	134	10	J24 - J44	132
K6	109	5	K2 - K12	110
K20	127	7	K14 - K28	123
K44	143	7	K30 - K44	140
L10	113	10	L2 - L24	115
L30	131	8	L26 - L44	130
M4	95	7	M2 - M16	96
M24	103	7	M18 - M32	106
M40	121	5	M34 - M44	119

* Excluding plots removed from the experiment, and continuity plots in each group.

In this table the groups of plots related to each continuity plot are also indicated. The mean annual yield per tree of each continuity plot over the six-year period is given in table 21, where it may be compared with the mean annual yield per tree of the related plots. The correlation between the mean of all related test plots and their companion continuity plots is high ($+ 0.721 \pm 0.025$), and compares very favorably with the correlations between actual and theoretical check yields of test plots calculated from systematically distributed check plots (table 19).

Such a correlation, if maintained, should result in a decrease of error, provided adjustment based upon the use of these plots as the theoretical check yield of the group of adjacent test plots is advisable. Using the preliminary yields of blocks I to M, adjustment of the yields of test plots was found to reduce their coefficient of variation 27.4 per cent of the unadjusted variation (from 13.43 per cent to 9.75 per cent), when the assumption was made that the yield of the theoretical check for each test plot is equal to the yield of the continuity plot in the same series. When the entire 195 plots are considered, the reduction in the coefficients of variation is 30.2 per cent of the unadjusted coefficient, from 13.03 per cent to 9.10 per cent. This reduction of variation is as great as that obtained by the use of check plots systematically replicated at more frequent intervals. With the coefficient of variation of 9.10 per cent, the odds are 30 to 1 that differences of about 11.7 per cent would be significant between 2 treatments of 4 noncorrelated plots each. An advantage exists over the systematic arrangement giving similar reliability, however, since a considerable number of plots are released for experimental purposes by the arrangement used. In case the yields of the plots in each of the groups about a continuity plot fail to be correlated in the future, the plots can be handled as if they were check plots distributed at irregular intervals. This would increase the errors of comparisons between adjusted yields but slightly, presumably to a point somewhere near that which would be given by the use of check plots distributed systematically at intervals of 8 plots.

THE ALLOCATION OF COMBINATION PLOTS

After the selection of 25 continuity plots, there remain 170 plots satisfactory for use as test plots, since 4 plots were temporarily eliminated because of injuries to the trees. The coefficient of variation of these 170 plots is 13.03 per cent. Two plots are to be used for special purposes. The 168 remaining plots have been divided into 42 treatment plots of 4 units each. The nature of these treatments is described elsewhere.[5]

The location of the plots for each treatment has been determined arbitrarily. The following considerations have had weight in the allocation:

1. *Preliminary yield:* In order to increase the reliability of the sampling an effort was made to select plots which represent the range of variation of the orchard for each treatment. With this in view, the mean yields of the plots were arranged in ascending order, and then separated

into 4 yield groups. Four plots were selected for each treatment in such a way that the mean yield of the 4 plots for 1922–27 was practically equal to the mean yield of the field.[18] The plan was to select 1 plot of each quartile group for each treatment, but it was impossible to follow this procedure exactly, since compromises were occasionally made necessary because of the importance of other factors.

2. *Satisfactory geographical distribution:* This factor was considered of great importance. If the yields of a plot after the beginning of the treatments are not correlated with the yields of that plot during the preliminary period, it would be desirable to have a random distribution of the unit plots of each treatment. This could be obtained most satisfactorily on the basis of random replication.

Another very important reason for obtaining a good geographical scattering of the unit test plots of the treatments is that it helps to protect the experiment from the local effects of accidental or of climatic injuries. These factors might be very important in affecting the yields of only a part of the planting. The scattering of the plots minimizes the chance that they will seriously affect the treatment means. In case the injury is so severe as to make the elimination of the records of a part of the field advisable, it is improbable that more than 1 unit test plot of a treatment would be discarded if the plots were distributed in this way. Some results would, therefore, be obtained from the remaining plots.

3. *Ease of visual comparisons:* The desire to compare certain treatments made it advisable to locate one replication of contrasting treatments in such a way that the comparable plots may be easily observed.

4. *Ease of cultural operations:* The grouping of plots which are to be cultivated alike is important in conducting an experiment of this kind, the success of which depends upon the reliability of the field operations. In general, such plots have been grouped in pairs one above the other from east to west, and occasionally in parallel pairs from north to south. This makes it possible to hasten the seasonal operations, such as the distribution of bulky fertilizers, as well as plowing and cultivation, which differ in the various treatments and which must be performed as nearly simultaneously as practicable.

The distribution of the 42 treatments is shown in table 22.

The preliminary yields of the unit plots making up the combination, or treatment, plots are given in table 23. In this table the yields are

[18] This is the method used by Lehmann.(27) It was independently suggested by Mr. F. D. Richey, in correspondence concerning the present orchard, who also suggested that it might be desirable to obtain nearly equal standard deviations for the different treatments. The method employed has approximated this condition, although the distribution has additional advantages, as indicated above.

arranged in ascending order to show the distribution which was obtained for the plots of each treatment. The actual yields of each plot are given in pounds (table 23, col. *3*), and also in the percentage which they constitute of the mean yield of the field as a whole for the six-year period (col. *5*). It may be seen that all the combination-plot means are approximately equal (cols. *4* and *6*).

TABLE 22

DISTRIBUTION OF TREATMENTS IN THE FIELD

Plot	Blocks									
	M	L	K	J	I	H	G	F	E	D
	Treatment No.									
2	16	23	30	26	29				10	12
4	C*	24	38	6	C				C	40
6	2	20	C	40	18				7	13
8	29	32	41	C	38				14	C
10	35	C	19	9	13				41	35
12	18	21	25	7	12				8	6
14	5	1	27	10	37	39			9	6†
16	4	3	31	14	42	C			11	6†
18	15	9	24	8	15	28			20	1
20	19	8	C	33	36	16			C	31
22	17	6	17	11	19	22	27		5	2
24	C	—	32	39	24	21	C		42	C
26	13	10	36	28	25	23	38			4
28	12	7	18	16	C	35	39			3
30	14	C	15	22	30	26	36			30
32	33	11	5	20	27	6	24	19		21
34	31	—	42	C	17	7	32	33		37
36	36	38	29	34	31	C	40	C		34
38	22	28	4	1	32	37	1	2		C
40	C	40	3	2	21	10	3	20		28
42	30	26	16	23	9	11	4	5		23
44	39	37	C	35	41	—	C	29		24
46						8	25	17		15
48						C	12	22		C
50						14	13	18		26
52						34	41	C		27
54						33	42	—		25

* C represents continuity plot.
† Demonstration plots.

FUTURE COMPARISONS

The statistical analysis of the reliability of the differences which may be obtained between treatments in the future trials can be made by several methods. However, the feasibility of comparisons between treatments based on differences between plots which were correlated in yield during the preliminary period of testing will be an object of future study. For the purposes of such comparisons, differences would be

TABLE 23

MEAN ANNUAL YIELDS PER TREE OF UNIT AND COMBINATION PLOTS, 1922–1927

Treatment No.	Plot numbers in order of increasing yields				Mean yield of respective unit plots, pounds*				Mean yield of combination plots, pounds	Mean yield of respective unit plots in per cent of mean yield of field				Mean yield of the combination plots in per cent
1	*2*				*3*				*4*	*5*				*6*
1	D18	J38	L14	G38	105	124	126	148	125.75	84	99	100	118	100.25
2	M6	D22	F38	J40	111	124	129	139	125.75	88	99	103	111	100.25
3	D28	L16	G40	K40	116	116	133	135	125.00	92	92	106	107	99.75
4	M16	K38	D26	G42	100	119	130	155	126.00	80	95	103	123	100.25
5	M14	E22	K32	F42	93	122	135	153	125.75	74	97	107	122	100.00
6	J4	H32	D12	L22	104	129	133	138	126.00	83	103	106	110	100.50
7	E6	L28	J12	H34	116	119	128	139	125.50	92	95	102	111	100.00
8	L20	J18	H46	E12	116	119	126	140	125.25	92	95	100	111	99.50
9	J10	L18	E14	I42	110	115	133	144	125.50	88	91	106	115	100.00
10	E2	L26	J14	H40	100	121	128	150	124.75	80	96	102	119	99.75
11	E16	L32	J22	H42	100	127	137	142	126.50	80	101	109	113	100.75
12	I12	M28	D2	G48	113	119	121	150	125.75	90	95	96	119	100.00
13	M26	I10	D6	G50	97	122	141	142	125.50	77	97	112	113	99.75
14	M30	J16	H50	E8	108	119	134	139	125.00	86	95	107	111	99.75
15	M18	I18	D46	K30	93	120	146	148	126.75	74	95	116	118	100.75
16	M2	H20	J28	K42	87	131	132	157	126.75	69	104	105	125	100.75
17	M22	I34	K22	F46	98	121	132	155	126.50	78	96	105	123	100.50
18	M12	K28	F50	I6	102	129	131	140	125.50	81	103	104	111	99.75
19	M20	K10	I22	F32	98	116	138	152	126.00	78	92	110	121	100.25
20	L6	E18	F40	J32	110	124	131	134	124.75	88	99	104	107	99.50
21	L12	H24	F48	I40	109	114	140	142	126.25	87	91	111	113	100.50

* These 4 subcolumns represent the 4 yield groups selected by the method described on pp. 137-138. Mean annual yield of all plots=125.7 pounds.

TABLE 23—(*Concluded*)

Treatment No.	Plot numbers in order of increasing yields				Mean yield of respective unit plots, pounds*				Mean yield of combination plots, pounds	Mean yield of respective unit plots in per cent of mean yield of field				Mean yield of the combination plots in per cent
1	*2*				*3*				*4*	*5*				*6*
22	H22	M38	J30	D32	116	120	130	139	126.25	92	95	103	111	100.25
23	L2	H26	D42	J42	103	115	138	146	125.50	82	91	110	116	99.75
24	K18	I24	G32	D44	112	115	133	144	126.00	89	91	106	115	100.25
25	D54	I26	K12	G46	108	117	122	155	125.50	86	93	97	123	99.75
26	J2	D50	L42	H30	103	115	128	153	124.75	82	91	102	122	99.25
27	G22	D52	I32	K14	120	122	126	137	126.25	95	97	100	109	100.25
28	J26	D40	H18	L38	110	122	132	137	125.25	88	97	105	109	99.75
29	M8	I2	K36	F44	79	113	146	165	125.75	63	90	116	131	100.00
30	K2	M42	D30	I30	96	114	136	152	124.50	76	91	108	121	99.00
31	D20	M34	K16	I36	105	119	129	150	125.75	84	95	103	119	100.25
32	L8	K24	G34	I38	112	121	135	136	126.00	89	96	107	108	100.00
33	H54	M32	F34	J20	114	127	128	135	126.00	91	101	102	107	100.25
34	L4	H52	D36	J36	106	114	136	147	125.75	84	91	108	117	100.00
35	M10	D10	J44	H28	98	128	135	138	124.75	78	102	107	110	99.25
36	K26	I20	M36	G30	104	125	135	140	126.00	83	99	107	111	100.00
37	I14	L44	D34	H38	108	126	128	142	126.00	86	100	102	113	100.25
38	G26	K4	I8	L36	103	119	129	147	124.50	82	95	103	117	99.25
39	M44	J24	H14	G28	107	119	132	141	124.75	85	95	105	112	99.25
40	J6	G36	L40	D4	99	127	138	140	126.00	79	101	110	111	100.25
41	K8	I44	E10	G52	99	126	130	150	126.25	79	100	103	119	100.25
42	I16	E24	G54	K34	113	118	136	140	126.75	90	94	108	111	100.75

* These 4 subcolumns represent the 4 yield groups selected by the method described on pp. 137-138. Mean annual yield of all plots=125.7 pounds.

obtained between pairs of the unit plots, the preliminary yields of each pair being in the same yield group as indicated by their position in the same vertical subcolumn of table 23, column *3*.

The magnitude of the differences between treatment means which would have been necessary for any given level of significance if the orchard, as finally laid out, had been under differential treatment from 1922 through 1927, can be determined from the available data. According to Student's[59] method for determining the average variance of a difference between the mean yields of the treatments as allocated above, $\sigma^2_{\bar{d}} = 3.9$ pounds. The probable error of the mean difference is, therefore, 1.33 pounds or 1.06 per cent of the mean yield per tree of all plots. If odds of 30 to 1 are desired for significance, this last figure is multiplied by 2.7 to obtain the average percentage difference between treatment means necessary; this is only 2.86 per cent of the mean annual yield per tree of all plots.

The correlation between plots in the same yield group cannot be expected to remain as high in the future years of the experiment as during the period of preliminary observation. In this event larger differences than those just noted will be necessary for significance. It seems probable, however, that a significant correlation will exist for many years, if not for the duration of the experiment, in which event it will have the effect of reducing the error of the experiment. If this correlation becomes small it is possible that methods of interpretation based upon adjustment of yields to check plots, or upon other methods, may lead to more accurate conclusions.

SOME RELATIONS OF THE VARIATION OF MEASUREMENTS OF TREE SIZE TO THE PLAN OF THE EXPERIMENT

Up to the present point the discussion of the plan of the experiment has been concerned chiefly with data of yields. Although yield data may be considered the most important criterion of the effects of the cultural treatments which are to be experimented with, they should be supplemented with other measures, particularly of the growth of the trees. According to the plans adopted, the area of cross section of the smallest point on the trunk and the volume of the top of the tree will be used as indexes of this response. Trunk measurements have been made annually since 1918, while careful top-volume measurements have been made since 1922.

Although it appears unnecessary for the purpose of the present paper to enter into a detailed analysis of the variation of the size of

TABLE 24

STATISTICAL CONSTANTS FOR MEASUREMENTS OF SIZE OF TREES IN NOVEMBER OF VARIOUS YEARS

Year, fall of	Mean*	Standard deviation	Coefficient of variation	Mean*	Standard deviation	Coefficient of variation
	Top volume of individual trees			Top volume per tree of plots		
	cubic feet	*cubic feet*	*per cent*	*cubic feet*	*cubic feet*	*per cent*
1922	374.9±1.16	67.0±0.82	17.87±0.226	376.3±1.93	39.9±1.36	10.61±0.366
1923	487.7±1.53	88.5±1.08	18.15±0.231	487.9±2.36	48.9±1.67	10.02±0.346
1924	654.0±2.01	116.0±1.42	17.74±0.224	653.2±3.18	65.9±2.25	10.09±0.348
1925	749.8±2.27	131.0±1.60	17.47±0.220	748.6±3.51	72.6±2.48	9.70±0.334
1926	848.2±2.58	149.0±1.83	17.57±0.222	849.1±3.77	78.0±2.66	9.19±0.316
	Area of trunk cross section† of individual trees			Area of trunk cross section† per tree of plots		
	square centimeters	*square centimeters*	*per cent*	*square centimeters*	*square centimeters*	*per cent*
1921	57.32±0.156	9.00±0.110	15.70±0.197	56.89±0.214	4.44±0.150	9.80±0.267
1922	74.99±0.219	12.65±0.155	16.87±0.212	74.85±0.285	5.90±0.201	7.88±0.270
1923	90.86±0.226	13.05±0.160	14.36±0.179	90.65±0.336	6.95±0.237	7.67±0.263
1924	102.80±0.255	14.75±0.181	14.35±0.179	102.30±0.382	7.90±0.270	7.72±0.265
1925	117.41±0.295	17.00±0.208	14.48±0.181	116.90±0.442	9.15±0.312	7.83±0.268
1926	127.22±0.314	18.10±0.222	14.23±0.178	126.90±0.447	9.25±0.316	7.29±0.250

* From grouped data.

† Area of cross section at a constant point on the trunk.

the trees as indicated by trunk size and volume of top, certain statistics will be of value, especially in showing some relations of these criteria to the plan of the experiment as laid out.

In table 24 are recorded the means, standard deviations, and coefficients of variation of the size measurements of trees and also the mean

TABLE 25

MEAN TOP VOLUME IN CUBIC FEET PER TREE FOR EACH PLOT, NOVEMBER, 1926

Plot	Blocks									
	M	L	K	J	I	H	G	F	E	D
2	733	758	757	780	927				874	868
4	725	769	868	703	858				954	921
6	845	761	815	723	947				761	829
8	776	750	784	817	934				909	1,014
10	755	777	800	869	1,014				936	936
12	735	825	818	801	926				848	814
14	853	887	876	791	921	1,115			881	783
16	812	831	888	804	855	992			596	710
18	787	827	825	803	921	917			860	895
20	699	821	935	893	945	1,001			836	811
22	803	780	891	969	995	983	901		802	871
24	764	*	857	944	858	1,005	898		761	799
26	759	799	778	819	857	979	829			889
28	862	823	863	840	863	965	973			839
30	756	754	847	887	854	930	866			877
32	799	791	799	904	845	797	918	1,071		784
34	738	*	845	780	942	866	919	916		732
36	750	790	843	848	947	901	975	976		813
38	727	801	817	771	806	807	927	747		809
40	791	819	826	867	848	878	854	865		830
42	696	730	885	822	894	882	789	905		811
44	710	813	832	850	796	*	873	896		849
46						815	885	963		944
48						843	849	901		750
50						840	840	895		924
52						829	920	1,006		847
54						855	959	*		823

* Plots omitted because of injury to trees.

size per tree of all plots, as determined in the fall of the years 1922 to 1926 inclusive. The abnormal trees eliminated from the records of yields are not included in the data. The coefficients of variation emphasize the relative uniformity of the size of the trees. However, large individual fluctuations are easily possible with the variation recorded. This is verified by a study of the mean size per tree of plots in the various years, examples of which are given for the fall measurements of 1926 in tables 25 and 26.

It may also be observed upon reference to tables 2, 11, and 24, that the variability in the size of tree at any one time of measurement is less than that of the yields in the same crop year. As in the case of yields, the means of the measurements of the trees in each plot show less variation than do the measurements of individual trees. The reduction in the coefficients is not, however, as great as that which would have been expected by the random combination of the same number of trees.

TABLE 26

MEAN AREA OF TRUNK CROSS SECTION IN SQUARE CENTIMETERS PER TREE FOR EACH PLOT, NOVEMBER, 1926

Plot	Blocks									
	M	L	K	J	I	H	G	F	E	D
2	111	109	104	117	129				132	134
4	111	114	112	105	129				134	142
6	118	114	113	107	128				121	127
8	119	113	109	129	133				130	139
10	115	120	127	123	141				135	136
12	113	125	122	117	130				135	129
14	126	121	137	120	146	153			132	128
16	122	122	131	120	135	148			103	114
18	122	117	120	127	149	136			133	131
20	115	115	126	127	143	142			128	126
22	129	122	133	127	134	140	140		129	127
24	132	*	127	124	129	137	133		118	125
26	132	126	117	131	137	128	129			128
28	127	122	141	127	123	127	134			128
30	128	121	133	139	132	127	130			137
32	120	119	128	126	138	122	129	144		132
34	114	*	135	119	139	132	135	124		125
36	122	119	133	123	133	136	137	132		126
38	107	117	114	123	122	128	136	125		125
40	128	118	134	124	118	123	126	123		130
42	118	110	120	118	136	123	131	132		128
44	112	121	132	130	113	*	127	131		133
46						118	134	147		139
48						127	132	125		126
50						131	128	128		137
52						129	134	143		138
54						135	142	*		131

* Plots omitted because of injury to trees.

It is apparent that the sizes of trees in the same plot are correlated, and that systematic influences affect their growth in various parts of the orchard.

A striking point in the data of table 24 is that during the years 1922 to 1926 inclusive, the variation of the size measures of trees and of plots fluctuates very little in the various years. This suggests that there is a high positive correlation in the sizes of trees in the various years. In fact, the coefficient of correlation between the mean top volume per tree of each plot in 1922 with that in 1926 has been found to be + 0.693

$\pm$ 0.025. The coefficient of correlation for the mean area of cross section of the trunk of the trees of each plot for the same dates is + 0.889 $\pm$ 0.010. These high positive correlations suggest that the relative size of trees in the different plots may tend to be more or less constant for a considerable period of time. This is in agreement with the observation upon orange trees of Webber,[64, 65, 66, 67] and Webber and Barrett,[68] and also with the conclusions of Sax.[45, 46]

TABLE 27

CORRELATION COEFFICIENTS OF YIELD OF TREES AND PLOTS WITH AREA OF TRUNK CROSS SECTION AND TOP VOLUME IN THE SAME CROP YEAR*

Year, spring of	Coefficients of correlation between yield and size: On the basis of individual trees	Coefficients of correlation between yield and size: On the basis of plot means
	Size measured by area of trunk cross section	
1923	+0.109±0.017	+0.220±0.046
1924	+0.233±0.016	+0.590±0.031
1925	+0.247±0.016	+0.307±0.044
1926	+0.278±0.016	+0.331±0.043
1927	+0.322±0.016	+0.342±0.043
	Size measured by top volume	
1923	+0.248±0.016	+0.335±0.043
1924	+0.478±0.013	+0.625±0.029
1925	+0.331±0.015	+0.453±0.038
1926	+0.286±0.016	+0.240±0.046
1927	+0.297±0.016	+0.341±0.043

* Total populations: 1,513 to 1,519 trees and 195 plots.

The relations of the sizes of the trees to their yields are indicated in table 27. In this table the coefficient of correlation between the cross-section area of the trunk, and also between the volume of individual trees, with the yields of the same trees in the same crop year, are presented. Similar coefficients are given for the correlation between the mean size and the mean yield per tree of plots for those years. The correlations are all positive and significant. This information indicates that in the trees of this planting there has been a tendency for the larger trees to be the higher producers.

The question naturally arises as to whether size of top or size of trunk is a better index of growth. The two measures are highly correlated in the records available at the present time. Thus in 1922 the coefficient of correlation between cross section and top volume, on a plot basis, was + 0.701 ± 0.025. In 1926 the same calculation rendered a coefficient of + 0.717 ± 0.023. On a tree basis the correlation between the two measures in 1926 was + 0.659 ± 0.010. However, the coefficients given in table 27 indicate that in most years the correlation between yield and top volume was only slightly higher than that between

TABLE 28

MEAN AREA OF TRUNK CROSS SECTION AND MEAN TOP VOLUME PER TREE OF CONTINUITY PLOTS AND MEAN OF PLOTS CONTIGUOUS TO EACH*

Location of continuity plots	Location of adjacent plots	Mean area of trunk cross section, in square centimeters per tree		Mean top volume, in cubic feet per tree	
		Continuity plots	Mean of adjacent plots	Continuity plots	Mean of adjacent plots
D8	D2 - D14	139	133	1,014	859
D24	D16 - D28	125	126	799	836
D38	D30 - D46	125	131	809	830
D48	D48 - D54	126	135	750	865
E4	E2 - E14	134	131	954	868
E20	E16 - E24	128	121	836	755
F36	F32 - F42	132	130	976	901
F52	F44 - F54	143	133	1,006	914
G24	G22 - G36	133	133	898	912
G44	G38 - G54	127	133	873	878
H16	H14 - H26	148	139	992	833
H36	H28 - H40	136	127	901	874
H48	H42 - H54	127	127	843	844
I4	I2 - I14	129	135	858	945
I28	I16 - I44	123	133	863	883
J8	J2 - J22	129	119	817	814
J34	J24 - J44	119	127	780	855
K6	K2 - K12	113	115	815	805
K20	K14 - K28	126	129	935	854
K44	K30 - K44	132	128	832	837
L10	L2 - L24	120	117	777	801
L30	L26 - L44	121	119	754	796
M4	M2 - M16	111	118	725	787
M24	M18 - M32	132	125	764	781
M40	M34 - M44	128	115	791	724

* Measured in November, 1926.

yield and area of cross section of trunk. It should be emphasized that the trees were growing fairly vigorously during this period. (See table 24 for mean size in the different years.) It seems possible that if accidental injury or the effects of treatments reduce the volume of the top greatly, top volume might become the better criterion.

At the conclusion of a preliminary period of testing, it is possible that size might be a better criterion of future productivity than yield and that the experiment might be planned more satisfactorily on that

TABLE 29

MEAN TOP VOLUME AND MEAN AREA OF TRUNK CROSS SECTION OF UNIT AND COMBINATION PLOTS, NOVEMBER, 1926

Treatment No.	Mean top volume, in cubic feet per tree					Mean area of trunk cross section in square centimeters per tree				
	Of respective plots*				Mean	Of respective plots*				Mean
1	895	771	887	927	870	131	123	121	136	128
2	845	871	747	867	833	118	127	125	124	124
3	839	831	854	826	838	128	122	126	134	128
4	812	817	889	789	827	122	114	128	131	124
5	853	802	799	905	840	126	129	128	132	129
6	703	797	814	780	774	105	122	129	122	120
7	761	823	801	866	813	121	122	117	132	123
8	821	803	815	848	822	115	127	118	135	124
9	869	827	881	894	868	123	117	132	136	127
10	874	799	791	878	836	132	126	120	123	125
11	596	791	969	882	810	103	119	127	123	118
12	926	862	868	849	876	130	127	134	132	131
13	759	1,014	829	840	861	132	141	127	128	132
14	756	804	840	909	827	128	120	131	130	127
15	787	921	944	847	875	122	149	139	133	136
16	725	1,001	840	885	863	111	142	127	120	125
17	803	942	891	963	900	129	139	133	147	137
18	735	863	895	947	860	113	141	128	128	128
19	699	800	995	1,071	891	115	127	134	144	130
20	761	860	865	904	848	114	133	123	126	124
21	825	1,005	901	848	895	125	137	125	118	126
22	983	727	887	784	845	140	107	139	132	130
23	758	979	811	822	843	109	128	128	118	121
24	825	858	918	849	863	120	129	129	133	128
25	823	857	818	885	846	131	137	122	134	131
26	780	924	730	930	841	117	137	110	127	123
27	901	847	845	876	867	140	138	138	137	138
28	819	830	917	801	842	131	130	136	117	129
29	776	927	843	896	861	119	129	133	131	128
30	757	696	877	854	796	104	118	137	132	123
31	811	738	888	947	846	126	114	131	133	126
32	750	857	806	919	833	113	127	122	135	124
33	855	799	916	893	866	135	120	124	127	127
34	769	829	813	848	815	114	129	126	123	123
35	755	936	850	965	877	115	136	130	127	127
36	778	945	750	866	835	117	143	122	130	128
37	921	813	732	807	818	146	121	125	128	130
38	829	868	934	790	855	129	112	133	119	123
39	710	944	1,115	973	936	112	124	153	134	131
40	723	975	819	921	860	107	137	118	142	126
41	784	796	936	920	859	109	113	135	134	123
42	855	761	959	845	855	135	118	142	135	133
Mean of all plots					849					127

* The order of the plots is that of increasing yields, as given in table 23.

basis. In the present experiment with Washington Navel oranges, it is anticipated that the growth responses of the trees to the different treatments can be interpreted with increased satisfaction because the preliminary records of size are available. It also seems possible that if size at the beginning of the differential treatments should be a better index of future yields than past yields, then size may be taken into account in the interpretation of yield data.

The relation of the mean size per tree of the plots to the future experiment, as planned, is indicated in tables 28 and 29. Table 28 shows the mean area of cross section of the trunks of the trees and their mean top volume in the continuity plots, and in plots contiguous to them, in a manner similar to the yield data of table 21. From the data of these tables it may be seen that there was considerable difference in the size of the trees in the different areas of the orchard at the start of the experiment, and that the mean size of trees in the plots chosen for the continuity treatment is on the whole correlated with the mean size of trees in contiguous plots.

In table 29 the size measurements per tree for 1926 are given for the plots of each treatment, and the means of the values for the 4 plots are also recorded. These means indicate that the plan of the experiment on the basis of yield during a six-year period has resulted in providing each treatment with a group of plots the mean size per tree of which was, generally, very uniform at the time the experiments were begun. However, some noticeable exceptions between treatment means do exist. If it should be indicated by future records that these differences are important in influencing yields, it may be possible that adjustment of yields by them might be advantageous.

SUMMARY

The fluctuations of yield of plants in experimental fields that are independent of the factors under trial, are of such importance that they must be taken into account in the plan of the experimental field and in the interpretation of the results obtained. Such difficulties are especially great in experimentation with trees because of the area of land involved and the long life of the plants. These considerations greatly increase the difficulty of securing a representative sample of the planting for each treatment.

Various methods have been proposed for the planning of experiments and interpretation of experimental results obtained under field conditions. Studies of uniformly treated fields and orchards have sug-

gested that the application of certain principles may depend on the individual characteristics of the field for their effect. The study of the characteristics of the individual orchard while under conditions of uniform treatment before the beginning of the experiment proper has been emphasized as having a bearing upon the plan of the future trials. The results of such a study are herein recorded.

The material consists of 199 plots of Washington Navel orange trees planted on land which had been originally uniformly cropped to grains under dry-farming conditions. The plots are of 8 trees each, arranged in a single row. Plot rows are separated by guard rows of trees of other citrus fruits. The rootstocks, buds, and nursery trees were carefully selected in an attempt to secure uniformity. The nursery trees were well mixed and planted at random. The irrigation system was arranged so that each plot could be separately irrigated in accordance with soil-moisture conditions. The orchard was maintained under as nearly uniform conditions as practicable until 7 crops (1921 to 1927 inclusive) had been harvested. At the end of that time the differential treatments were put into effect.

It was observed that the distribution of yields of trees approached that of the normal frequency curves in six of the seven years for which studies were made. In the first year of bearing (1921), the distribution was not normal. The mean yield per tree of plots in all years was of practically normal distribution. The use of statistical formulas based upon an assumption of normality in treatment of most of the data is believed warranted.

Studies of variability of the yields of individual trees indicated a very high coefficient of variation for 1921. Coefficients for the six remaining years averaged 25.4 per cent, a relatively low figure, especially in consideration of the plan of planting. When the yields per tree of the individual plots were considered for the various years, the variation was reduced materially, but not to the extent which would be anticipated on the basis of random sampling. This phenomenon was due to a positive correlation of considerable magnitude which was found to exist between yields of trees in the same plots. Emphasis is placed upon systematic variations due to soil influences.

It was observed that the yields of all years except 1921 tended to have about the same degree of gross variation. Consideration of the mean annual yield per tree of plots in the various years, expressed in percentage of the mean annual yield of all trees, showed that there was a tendency for individual plots to yield about the same relative amount in all years except 1921. This tendency was measured by the use of interannual correlations of yields of individual trees and of plots. In this study, the yields of 1922 and of 1923 were not as highly or as consistently correlated with yields of later years, as the yields of these later years were correlated with each other. The coefficients of variation of yields of 1922 and 1923 were also higher.

It was apparent that the use of yield data for the first year of production would not have led to results which would have been duplicated in succeeding years if the orchard had been under differential treatment at the time. The yields of 1921 were, therefore, not used in studies of various possible plans for the future experiment which are reported. The yields for the six-year period, 1922 to 1927 inclusive, are, however, rather consistent, and are used as an index of the productivity of each plot during the preliminary period. The variation of the six-year mean yield was found to be less than that of the yields of individual years, but not so low as that which would be expected on the assumption of random sampling. This effect is due to the positive interannual correlation existing between yields of the same plots in the different years.

The calculations made upon data obtained during the preliminary period of observation, during which the orchard may be regarded as a uniformity, or blank, experiment, seem to justify the expectation that an experimental plan which would have been most reliable in the preliminary period would also be most efficient in the future. The records of mean yields for six years were, therefore, subjected to a study to determine the effect of various plans upon variability of test plots, and the magnitude of the differences between the mean yields of combination, or treatment, plots which would be necessary to insure significance.

It was shown that the use of single plots for each treatment would be unsatisfactory, owing to the great differences which occur normally between them. Increase of the area devoted to each treatment by combining contiguous plots decreased natural variations between treatments, but this decrease was not rapid because of correlation between yields of adjacent plots due to systematic influences of soil fertility. The combination of systematically replicated plots for each treatment, however, reduced the variation of treatments approximately according to the expectations of random sampling. The size of the combination plots necessary to insure a reasonable degree of significance under these conditions was found to be larger than desirable.

Certain aspects are presented of the theory of the use of check plots in attempts to reduce systematic variations due to fluctuations in the fertility of the soil. Attempts have been made to determine the effects of adjustment of test-plot yield by means of systematically replicated check plots. Checks were located at various intervals, and several of the more common methods of calculating the theoretical check yields of the intervening test plots were used. The greatest reduction in variation of adjusted yields was found when check plots were located at frequent intervals and an interpolation, or ''grading,'' formula was used for the calculation of theoretical check yields of test plots. Differences between treatment means necessary for a moderate degree of significance were also calculated, and showed corresponding decreases. It is pointed out, however, that the use of check plots requires a large area of land which might be used for increased replications of the treatments. By assuming that a constant number of hypothetical treatments were to be tried upon the area studied, the number of test plots devoted to each varying according to the number of checks employed, it was found that the most favorable gain in reliability obtained by adjustment to checks was slightly greater than that obtained by increased replication of test plots for each treatment which was made possible by the elimination of the check plots.

It was observed that the use of differences between yields of test plots, adjusted by means of check plots, and the yields of the check plots themselves reduced systematic variation in yield due to soil fluctuations. Rather accurate conclusions can be drawn by this method as to the significance of small differences in yield between any 1 treatment and the check plots. This advantage, however, vanishes when it is desirable to compare 2 treatments by means of the difference between their adjusted yields and the check yield.

The use of methods of differences between test plots was found by means of Student's[59] formula to give about the same reliability, with many treatments and a small number of systematically distributed replicates for each treatment, as that obtained in direct comparisons between the means of the treatments. This indicates that little or no correlation exists between the ''paired'' plots of a replication series under such conditions, and that the last term in the formula for the variance of a difference, $\sigma_1^2+\sigma_2^2-2r_{1\cdot2}\sigma_1\,\sigma_2$, is practically equal to zero.

The adjustment of yields of test plots by means of other contiguous test plots is discussed. It is believed that the value of the use of such methods can be obtained after the differential trials are in effect.

The use of yields of test plots, obtained under conditions of uniform culture, for the adjustment of yields of the same plots after the different treatments have gone into effect is discussed. There are certain aspects of experimental work with trees which indicate that interannual correlations of yields with orchard material may be more consistently positive than with annual plants. The calculations made upon the data of this orchard suggest that they may be important. It is believed that methods may be used to take advantage of whatever correlations may be found in the future between yields prior to and during the actual period of testing the various treatments. It is probable that pairing plot yields of individual treatments may be carried out in the future trial upon the basis of their correlated yields during the preliminary period of testing.

As a result of these studies a plan for the experimental orchard under consideration has been adapted to the practical ends desired. Four plots are used for each treatment and are chosen on the basis of preliminary yield. Check plots designated as continuity plots, are provided as a precautionary measure, and to obtain certain information as to orchard experimental technique. The check plots are also arranged on the basis of preliminary yields in such a way that they are a fair sample of the area contiguous to them at the time of starting the differential treatments, with the idea of judging the relative productivity of that area. Adjustment of yields of test plots by the use of the continuity plots, under the conditions existing during the preliminary testing, gave an increase in reliability comparable to that given by the use of systematically replicated check plots at more frequent intervals.

The 4 test plots allocated to each treatment were chosen on the basis of their mean annual yield per tree for the six-year period in such a way that the mean yields of the sets of 4 plots for this period were approximately equal. Wherever feasible, 1 plot was chosen from each quartile group of the frequency distribution, forming 4 replication series. The importance of a good geographical scattering of the replicates and of certain features which are important from a cultural point of view was also recognized in selecting the replicates for each treatment. With the high correlation existing between yields of plots in the same yield group during the preliminary period, the use of Student's[59] method for the determination of the average variance of a difference between treatments indicated that relatively small differences would be significant with a considerable degree of reliability. The reliability of small differences in the future as determined by this method depends upon the correlation between yields of plots in the 4 yield groups. Should this correlation vanish entirely, a possibility which does not appear imminent, the more common methods of interpretation may be used, such as adjustment by means of check plots or contiguous test plots, or by comparisons between unadjusted yields.

Some relations of the plan of the experiment, as developed on the basis of past yields, to the variability of measures of tree size are presented. Yield was somewhat more variable than the volume of the top of the tree, or the area of the cross section of the trunk. Interannual correlations between the size measurements were high. These correlations emphasize the value of a knowledge of the size of trees before the beginning of an experiment as an aid in the interpretation of the effects of the treatments. Since the size of these trees at any one period was correlated with their yield in the same crop year, a knowledge of the size at the beginning of an experiment might logically be used as a basis of pairing trees or plots for comparison of yields by methods of differences. The tree-size relations of the plots of the experimental orchard, as planned on the basis of yields, are presented. The data indicate that, on the whole, the mean size of the trees devoted to each treatment approaches the mean of the orchard. Occasional differences of considerable dimensions do exist, however. It is possible that future records may show that some recognition of these differences should be made and that some adjustment may be desirable.

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APPENDIX

TABLE OF ODDS*

Difference from mean in terms of probable error	Difference between two results in terms of probable error	Odds against such a difference occurring under uniform conditions
With difference in either direction		
1.00	1.41	1 to 1
1.25	1.76	3 to 2
1.44	2.03	2 to 1
1.71	2.41	3 to 1
1.90	2.68	4 to 1
2.00	2.83	9 to 2
2.05	2.87	5 to 1
2.50	3.53	10 to 1
2.93	4.13	20 to 1
3.00	4.24	22 to 1
3.20	4.51	30 to 1
4.00	5.66	140 to 1
4.90	6.93	1,000 to 1
5.00	7.07	1,350 to 1
With difference in one direction only		
1.00	1.41	3 to 1
1.25	1.76	4 to 1
1.44	2.03	5 to 1
1.58	2.23	6 to 1
1.71	2.41	7 to 1
1.81	2.55	8 to 1
1.90	2.68	9 to 1
2.00	2.83	10 to 1
2.48	3.50	20 to 1
2.70	3.81	30 to 1
2.89	4.07	40 to 1
3.00	4.24	44 to 1
3.03	4.28	50 to 1
3.44	4.85	100 to 1
4.00	5.66	290 to 1
5.00	7.07	2,700 to 1

* From Wood, T. B. The interpretation of experimental results. Jour. Bd. Agr. [London] Sup. **17**:15–32. 1911.