UNITED STATES DEPARTMENT OF AGRICULTURE

DEPARTMENT BULLETIN No. 1377

Washington, D. C. ▼ March, 1926

A STUDY OF THE VALUE OF CROP ROTATION IN RELATION TO SOIL PRODUCTIVITY

By

WILBERT W. WEIR, Associate Soil Technologist
Bureau of Soils

CONTENTS

WASHINGTON
GOVERNMENT PRINTING OFFICE
1926

UNITED STATES DEPARTMENT OF AGRICULTURE

DEPARTMENT BULLETIN No. 1377

Washington, D. C. ▼ March, 1926

A STUDY OF THE VALUE OF CROP ROTATION IN RELATION TO SOIL PRODUCTIVITY

By WILBERT W. WEIR, *Associate Soil Technologist, Bureau of Soils*

CONTENTS

INTRODUCTION

The maintenance of soil productivity depends largely on those factors which are commonly referred to as farm practices, notably cultivation of the soil, crop rotation, the use of fertilizers and agricultural lime, land drainage, and irrigation. Taking into consideration all kinds of soils and the more or less established systems of agriculture, three of these farm practices assume outstanding prominence: (1) Cultivation; (2) rotation of crops; and (3) the use of fertilizers.

Cultivation of the soil includes the preparation of a suitable seed bed and any subsequent stirring of the soil to kill weeds or to conserve soil moisture. The preparation of the seed bed, a practice which has come down to us from times immemorial, is universally recognized as a necessary first step in the production of farm crops

60635—26†——1

regardless of the producing power of the soil, whereas the importance of subsequent cultivation or intertillage was not given general recognition in practical farming until near the close of the eighteenth century (*14, pp. 148–175*).[1]

Crop rotation—the growing of different kinds of crops in recurring succession on the same land—has been recognized by early agricultural scientists to be the foundation of the improvements in agriculture which took place in England, in large portions of continental Europe and in the United States during the last part of the eighteenth and especially during the last century (*9, p. 195*). The benefits to be derived from the growing of leguminous crops in alternation with the cereals were distinctly recognized by the ancient Romans (*2, 18*); and the benefits of growing intertilled turnips or root crops in rotation with barley, clover, and wheat were discovered about, or after, 1730, in England.

Fertilizers such as dung, marl, ashes, and green-manure crops were used in soil improvement in ancient times; but it was not until after about 1840 that chemical or manufactured fertilizers were known or received much recognition. In modern times, especially in the older agricultural sections, the use of manure or chemical fertilizers, or both, is commonly regarded as the paramount farm practice to assure successful crop production or to maintain the productivity of soils. The term fertilizer, as it is used in this bulletin, includes farm manure and chemical fertilizers.

The fact that the value of fertilizers may be easily and definitely demonstrated on certain soils which are in need of special kinds of fertilizers or on soils low in producing power because of exhaustive cropping, has established the value of chemical fertilizers, particularly in sections where fertilization practices have become established. And thus it seems logical to credit the bulk of crop yields in these sections to the fertilizers used. It is not assumed that the value of crop rotation is entirely overlooked. On the contrary, the fact that in most of these older sections, where systems of farming have become more or less established, crop rotation is commonly practiced gives evidence of the recognition of its value.

The effects of crop rotation on yields are manyfold: Rotation aids in controlling weeds and certain crop pests and diseases. It may render manure and chemical fertilizers more effective. It increases the soil supply of organic matter and nitrogen, improves tilth, and conserves the soil reserve of plant nutrients; and the different crops in themselves may exert beneficial effects on those which follow.

The total effects of rotation when conjoined with fertilizers may be measured by determining the difference in the yields obtained with fertilizers in rotation and with the same fertilizers in continuous culture; that is, when a crop is grown continuously on the same land. The questions now arise: (1) What is the value of crop rotation as compared with the use of fertilizers in crop production? (2) When a farmer combines the use of fertilizers with rotation of crops, do these two farm practices when thus conjoined produce additive effects in promoting increases in crop yields? (3) What are the comparative values of crop rotation and fertilizers in maintaining and increasing soil productivity?

[1] Reference is made by number (*italic*) to "Literature cited" p. 68.

There is another aspect of the question regarding the effects of rotation on crop yield, which is perhaps the more important one; namely, the value of crop rotation in relation to the national food-production problem. From this point of view, cultivation of the soil, crop rotation, and the use of fertilizers are still to be regarded as the dominant farm practices not only in maintaining but in increasing our Nation's food supply. As regards its maintenance, much will depend on good cultivation and judicious use of fertilizers. But what of the value of crop rotation? As regards increasing our food supply, how much can the average yield of wheat or corn, for example, be increased by improving present methods of cultivation? How much additional increase can be effected by establishing more systematic crop rotation or by improving the rotations now being practiced? And how much can these increases be augmented still more by a more general and intelligent use of manure and chemical fertilizer?

PRIMARY OBJECTS OF STUDY

Inasmuch as any attempt to answer these questions, especially as regards crop rotation, without any specific knowledge of the value of rotation may result in bare speculation, it seems logical to study experimental data with a view, in each case (1) to determinining some more or less definite measure of the value of rotation in crop production, and (2) to comparing its beneficial action with that of fertilizers in maintaining and increasing soil productivity. These, briefly stated, are the primary objects of this study.

METHOD OF STUDY

Whatever method may be applied to experimental data in evaluating absolute or relative values of crop rotation and the use of fertilizers in crop production and in maintaining and increasing soil fertility, at least four conditions must be met experimentally before such values can be ascertained: (1) The value of the effects of crop rotation and the use of fertilizers must be based on long-continued fertility experiments; (2) in any particular case a crop must be grown with and without fertilizers in continuous culture and in rotation and on the same type of soil; (3) comparable yields must represent the same seasonal effects; and (4) the fertilizer treatment given a crop in rotation should be similar to that given in continuous culture.

The fact that crop rotation is a system of cropping which extends over a longer or a shorter period of years necessitates a consideration of the long-time fertility tests. A fertilizer may be applied before, at, or after planting time, and the results may be measured, in part at least, the same year. Such a demonstration can not be made with crop rotation. A fertilizer is a definite, physical object which can be measured, weighed, and applied to a soil. A rotation, on the other hand, is something abstract, in that it possesses no materiality or has no physical reality as does a fertilizer. It is, rather, a concept connoting the attributes of a particular system of cropping, whose effects, in general, may be measured only after a series of years.

From the four differently treated plots furnishing the basic data for this study are obtained, in each case, the following comparable crop yields; the average yield without fertilizer and rotation (check-plot yield in continuous culture), the yield resulting from the use of fertilizer alone (yield from fertilized plot in continuous culture), the yield in rotation without fertilizers (check-plot yield in rotation), and the yield in rotation with fertilizers (yield from fertilized plot in rotation).

Though this study calls for a consideration of the long-time soil-fertility experiments, yet the data of all such experiments can not be used, since in some instances, those at State College, Pa., for example, none of the crops which make up the rotation are grown in continuous culture (*3*).

The soil is an important factor in determining the comparability of continuous-culture and rotation yields in each experiment. Fortunately, in the long-time fertility experiments involving yields in rotation and continuous culture, practically the same kind of soil is under test in each case.

The seasonal effects on crop yields are well known and are usually given careful consideration when comparisons are made of crop yields. In some of the long-continued experiments the rotation plots are repeated as many times as it is necessary to give the yield of each crop each year; whereas in other experiments there is no replication of the rotation plots. In the case of the former experiments, an average yield in continuous culture for a series of years is comparable with the average yield of the same crops grown in rotation for the same period of years. Such yields are comparable, since they include the same number of years and the same seasonal effects. On the other hand, in those experiments where the rotation plots are not repeated, an average yield for a series of successive years in continuous culture is not comparable with an average yield of the same crop grown in rotation for the same period, since the rotation average represents a less number of years and reflects a different combination of seasonal effects. In such cases comparisons between particular yields in continuous culture and rotation may be made by taking the average yield of a crop grown in rotation and comparing it with the average of the yields obtained during the same years in continuous culture. At Rothamsted, for example, wheat is grown continuously on the same land and also in a four-year rotation which is represented by only a single series of plots. Experimental data for 72 years include 18 wheat yields in rotation and 72 yields in continuous culture. An average yield of the 18 crops grown in rotation is comparable with an average yield in continuous culture only when the latter average is obtained from the 18 yields which have been obtained in continuous culture during the same years that wheat has been grown on the rotation plots.

Inasmuch as this study involves a consideration of not only the effects that rotation and the use of fertilizers have on crop yields when acting independently of each other, but also their conjoint effects, as compared with their single effects, it is important that the crops in rotation be fertilized the same as in continuous culture. This raises the question as to the kind of chemical fertilizers that should be selected for comparable yields.

In some of the long-time experiments are included the results from chemical fertilizers which carry one, two, or all three of the major, nutrient elements; that is, nitrogen, phosphorus, and potassium. In this study results from complete fertilizers have been selected, because it is to be observed that, in these long-time experiments, complete fertilizers are more consistently effective in maintaining and increasing soil productivity than those in which one or two of the major fertilizing constituents are lacking. Thus it seems logical, especially since results from manure are also included, to compare the value of rotation with the effectiveness of those chemical fertilizers which are most efficient in soil-fertility maintenance. The details concerning the composition of the fertilizers and the quantity applied are brought out in the discussion of each of the experiments which have been selected for study.

EXPERIMENTS SELECTED FOR STUDY

From all published, official data it has been possible to select six groups of long-time experiments (Table 1) which satisfy the conditions discussed in the foregoing paragraphs. They are named in chronological order according to the dates when comparable yields begin, though in some cases the experiments were begun several years before the dates indicated. The results of these experiments are discussed in the order named.

TABLE 1.—*Long-time continuous-culture and rotation experiments*

Location	Dates of comparable yields	Crops involved
Rothamsted, Hertford County, England	1851 to 1921, inclusive	Wheat and barley.
Columbia, Mo	1889 to 1918, inclusive	Indian corn, oats, wheat and timothy.
Wooster, Ohio	1894 to 1918, inclusive	Indian corn, oats, and wheat.
Germantown, Ohio	1903 to 1918, inclusive	Tobacco.
Urbana, Ill. (Morrow plots)	1904 to 1917, inclusive	Indian corn.
Florence, S. C	1914 to 1919, inclusive	Cotton.

DISCUSSION OF EVALUATION METHODS

In evaluating the effects of rotation and of fertilizers on crop yields and in maintaining and increasing soil fertility, at least three methods suggest themselves. A discussion of these methods follows.

In order to make the discussion concrete, the average of the results obtained with farm manure on corn at Columbia, Mo., will be used, as follows:

Yield without manure and rotation (cultivation alone, *c*)—22.4 bushels.

Yield with manure but without rotation (*c* and fertilizer, *f*)—37.1 bushels.

Yield in rotation without manure (*c* and rotation, *r*)—37.5 bushels.

Yield in rotation with manure (*c*, *r*, and *f*)—47.7 bushels.

For convenience, continuous culture without fertilizer or manure will be called simply *cultivation*, including the tillage necessary in the preparation of the seed bed and any subsequent cultivation, whose effect will be indicated by small *c*. Rotation and fertilizer effects will be indicated by small *r* and *f*, or capital *R* and *F*, respectively, indicating different values for rotation and fertilizers. In all cases the effects of cultivation, rotation and fertilizers will be evaluated in terms of yield units, as absolute values, representing either actual yields or increases effected.

The increase effected in the yield of a particular crop by rotation alone when it is combined with cultivation may not be equal to the increase effected when rotation is added to the combined practices of cultivation and the use of fertilizer. In like manner the increase effected by the use of fertilizer may differ. Thus, small *r* will indicate the effects of rotation when it is combined with cultivation alone, and capital *R* will indicate its effects when rotation is added to the combined practices of cultivation and the use of fertilizer. The value for *R* (with fertilizer) may be either greater or less than the value for *r* (without fertilizer). In a similar manner, small *f* will indicate the effects of fertilizer when it is used without rotation, and capital *F*, the effect when the use of fertilizer is added to rotation. In the data which follow, it will be shown that the value for *F* (with rotation) is often greater than the value for *f* (without rotation).

The different values for rotation and for the use of fertilizer may be illustrated in the following manner, using the same results with manure on corn at Columbia, Mo.:

Case I

	Bushels
Yield in continuous culture without any fertilizer (*c*)	22. 4
Gain effected by use of manure in absence of rotation (*f*)	14. 7
Additional gain effected when to use of manure is added rotation (*R*)	10. 6
Yield resulting by adding rotation to the use of manure	47. 7

Case II

	Bushels
Yield in continuous culture without any fertilizer (*c*)	22. 4
Gain effected by rotation in absence of manure (*r*)	15. 1
Additional gain effected when to rotation is added the use of manure (*F*)	10. 2
Yield resulting by adding the use of manure to rotation	47. 7

FIRST METHOD, INVOLVING ASSUMPTIONS

Ordinarily, the evaluations of rotation and of fertilizers, as effecting increases in crop yields, are calculated as follows:

Manure without rotation, $37.1-22.4$; that is, $cf-c$, or 14.7 bushels.

Rotation without manure, $37.5-22.4$; that is, $cr-c$, or 15.1 bushels.

Manure and rotation conjoined, $47.7-22.4$; that is, $cfr-c$, or 25.3 bushels.

And further, the effect of manure in rotation is ordinarily measured as the difference between 47.7 and 37.5; that is, $cfr-cr$, or 10.2 bushels. Since the conjoint action of rotation and manure has effected an increase of 25.3 bushels in the yield, it seems reasonable, in order to determine what portion of this total increase should be credited to rotation, to take the difference between 25.3 bushels and 10.2 bushels, thus arriving at a difference of 15.1 bushels as a value for the effect of rotation (*R*) when conjoined with the use of manure.

Thus, according to this method, rotation without manure effected an increase of 15.1 bushels, whereas manure without rotation effected an increase of 14.7 bushels. When acting conjointly, rotation is given a value of 15.1 bushels of increase, and manure, a value of 10.2 bushels.

The above method is subject to criticism, because two assumptions are involved. First, in arriving at the values of the effects of rotation (r) and manure (f) when acting independently of each other, it is assumed that the effects of cultivation are the same when conjoined with rotation or manure as when it is acting alone. The same assumption is made in evaluating the conjoint effects of rotation and manure. This assumption, in all probability, does not distort the true values of rotation and manure very much one way or another, since cultivation is the one factor which is involved in all the yields compared; and, moreover, there seems to be no way to determine whether or not the effects of cultivation represent the same value in all the comparable yields.

The second assumption made is that the effect of rotation (R) when conjoined with manure is the same as when it is acting independently of manure. It seems reasonable to believe that rotation must exert some effect on manure, and that manure, in turn, must have some effect on the efficiency of rotation. In other words, it seems highly probable, as analysis seems to show, that there is an interaction between rotation and the use of manure when these practices are combined.

If the formula $cfr-cr$ (47.73 – 37.5) is correct in arriving at a value of 10.2 bushels of increase for manure (F) when conjoined with rotation, it is just as logical and correct to use the formula $cfr-cf$ (47.7 – 37.1) to arrive at a value of 10.6 bushels for the effects of rotation (R) when this practice is conjoined to the use of manure. In a previous paragraph, the effect of rotation has been evaluated at 15.1 bushels of increase when conjoined with manure, or the same as when rotation acts in the absence of manure. According to the second formula, the rotation value is not the same, but less by 4.5 bushels.

It is a fact that must be accepted that the conjoint effects of rotation and manure resulted in an increase, in this particular experiment, of 25.3 bushels over cultivation alone. In arriving at this value no assumptions are made. However, it can not be determined just how much of this total increase should be credited to rotation or to manure. According to the above analysis the value for rotation (R), when joined to the use of manure, must lie somewhere between 10.6 bushels and 15.1 bushels; and the value for the use of manure (F), when joined to rotation, between 10.2 bushels and 14.7 bushels.

SECOND METHOD

Another method that suggests itself in this study is to consider the effects of cultivation, rotation, and fertilizers from the point of view of farm practices, and to evaluate their effects on crop yields in terms of the differences in the average yields obtained. Thus, taking the same Missouri results with manure on corn, as used for illustration, the practice of cultivation alone resulted in an average yield of 22.4 bushels per acre; of combining the use of manure with cultivation, 37.1 bushels; of combining rotation of crops with cultivation, 37.5 bushels; and of combining all three practices, 47.7 bushels per acre. Since in these evaluations no assumptions are involved, this second method is the first of two methods used in this study.

The practice of using manure without rotation resulted in an increase of 14.7 bushels over cultivation alone, and the practice of rotation of crops without the use of manure resulted in an increase of 15.1 bushels over cultivation alone. Hence, under the conditions of the Missouri test the practice of rotation without the use of manure produced practically the same effects as the practice of using manure without rotation.

The practice of conjoining rotation of crops and the use of manure resulted in a gain of 25.3 bushels over cultivation alone, which is within 5 bushels of the sum of the separate effects of rotation and the use of manure. In other words, when under the conditions of the experiment the practice of crop rotation and the use of manure are conjoined, the effects produced on the crop yield were nearly fully additive, or nearly as large as the sum of their separate effects.

The formula $cr-c$ gives the value for the effects of rotation when practiced independently of the use of fertilizers. This value of rotation (r), in the experiment cited, is equal to 15.1 bushels of increase.

When the use of manure and rotation are practiced conjointly, from $cfr-cf$ we derive another value for rotation, being the actual increase effected when to the use of manure is added rotation of crops. This value for rotation (R) includes not only the effects of rotation in itself but, in addition, any effect that it may have on the condition of the soil or in increasing or decreasing the efficiency of the manure as compared with its effects when acting in the absence of rotation. In this case the value for rotation (R), in the illustration used, is equal to 10.6 bushels of increase.

The formula $cf-c$ gives the value for the effectiveness of the use of manure when practiced in the absence of rotation. This value for manure (f), in the experiment named, is equal to 14.7 bushels of increase.

From the formula $cfr-cr$ we derive another value for the effects of the use of manure, being the actual increase effected when to rotation is added the use of manure. This value for the use of manure (F) includes not only its direct nutritive value (be it greater or less than when it is used without rotation), but, in addition, any interactive effects due to conjoining the use of manure and rotation of crops. In this case the value for the use of manure (F), in the illustration used, is 10.2 bushels of increase.

THIRD METHOD

The method selected for evaluating the beneficial effect of rotation and fertilizers involves only a comparison of the effects of the practices of rotation and of the use of fertilizers on crop yields, and it does not show the effects resulting from rotation and the use of fertilizers in relation to the maintenance and increasing of soil productivity. This necessitates a somewhat different method of study.

Maintaining soil productivity implies holding or keeping up the productive power of the soil. In case of any one of the long-time experiments, the average yield of a crop at the beginning of the experiment must be taken as the yield to be maintained, or it may be termed the maintenance yield, from which the values of rotation and the use of fertilizers in fertility maintenance are to be reckoned, and from which rotation and fertilizer values in increasing productivity are to be measured.

A concrete illustration may help to make clear the application of this method. The same results obtained with manure on corn at Columbia, Mo., as used in the previous discussions, will be used. In Figure 1 are given the average yields per acre for the period, 1894 to 1918, in a semidiagrammatic form, showing the comparable average yields and their relative positions with reference to the maintenance yield of 33.5 bushels, the 5-year average yield at the beginning of the experiment, for the period, 1889 to 1893, inclusive.

It is to be observed that cultivation alone (*c*) fell short 14.5 bushels in maintaining the yield obtained at the beginning of the experiment; the practice of combining the use of fertilizer (manure) with cultivation (*cf*) resulted in a slight gain of 0.3 bushel, above the maintenance yield; the practice of combining rotation with cultivation

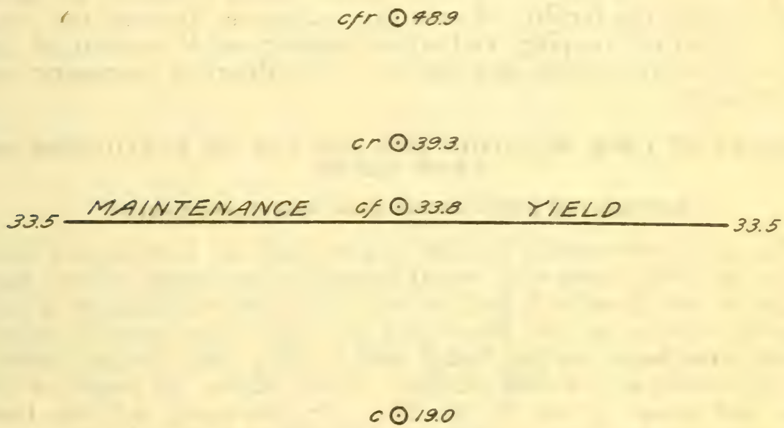

FIG. 1.—A representation of the results of a series of long-time fertility tests on corn at Columbia, Mo., showing the relation of comparable yields to the maintenance and the increasing of soil productivity. Small *c* indicates the effects of cultivation alone; *f*, the effects of fertilizer (manure); and *r*, the effects of crop rotation

(*cr*) increased soil productivity by 5.8 bushels per acre; and the practice of combining cultivation, rotation of crops, and the use of manure (*cfr*) increased the productivity of the soil by 15.4 bushels (48.9 − 33.5).

The difference between the yields of 48.9 bushels (*cfr*) and 19.0 bushels (*c*) simply gives a measure of the difference in the producing power of the soil as effected by the two different practices indicated. On the other hand, the difference between the yield of 48.9 bushels (*cfr*) and 33.5 bushels (maintenance yield) measures the effects of the conjoint action of cultivation, rotation, and fertilization in increasing soil fertility. Likewise, the true measure of the value of manure in increasing productivity during the period of the experiment is not the difference between the yields of 33.8 bushels (*cf*) and 19.0 bushels (*c*), but the difference between 33.8 bushels (*cf*) and 33.5 bushels (maintenance yield). The same argument holds in case of rotation.

In this particular experiment, it is to be noted that both rotation (*r*) and manure (*f*) maintained soil productivity. Since the yield to be maintained is 33.5 bushels, the full effectiveness of rotation alone, in its relation to fertility maintenance, may be expressed as 117.3 per cent; and that of manure alone, 100.9 per cent. Thus the relative value of rotation, as compared with manure, in maintaining productivity may be expressed as 116.2 per cent.

As regards increasing soil productivity, when the use of manure is combined with cultivation the increase in yield, resulting from these combined practices, is only 0.3 bushel (33.8 – 33.5). When rotation is combined with cultivation the increase is 5.8 bushels. But when rotation and the use of manure are conjoined, the increase in yield is 15.4 bushels, which is nearly 152.5 per cent greater than the sum of the increases resulting from rotation and fertilization when practiced independently of each other.

The long-time experiments included in this study have to do with six major crops, and the average yields at the beginning of the experiments vary from rather low to medium—yields which are accepted as indicating the fertility of soils that have gone through the "virgin" period of cropping, and which make possible a study of the values of crop rotation and the use of fertilizers in increasing soil productivity.

EFFECTS OF CROP ROTATION AND THE USE OF FERTILIZERS ON CROP YIELDS

ROTHAMSTED EXPERIMENTS WITH WHEAT AND BARLEY

The more systematic fertility experiments at Rothamsted were begun in 1843; those with wheat grown in continuous culture were begun on the Broadbalk field in 1843, and those with barley in continuous culture, on the Hoos field in 1852. The rotation experiments were begun on the Agdell field in 1848—the rotation consisting of rutabagas (Swedish turnips), barley, clover (or beans) or fallow, and wheat (*4, pp. 31, 70, 190*). In this study only the four-crop rotation has been considered: Rutabagas, barley, legumes, and wheat, grown in the order named. From the above dates it is to be observed that comparable wheat yields begin with the year 1851, and those of barley with 1853. Since the rotation plots are not repeated, wheat and barley are grown every fourth year on the Agdell field; on the Broadbalk and Hoos fields, respectively, they are grown every year. On the rotation plots rutabagas receive all the fertilizer; on the continuous-culture plots, wheat and barley are fertilized annually.

Having determined the values of crop rotation and of fertilizers in increasing soil productivity, these values, although calculated from the comparatively low maintenance yields of the long-continued experiments, should serve just as well in emphasizing the values of rotation and of fertilizers in fertility maintenance under conditions of higher productivity.

One more word in reference to rotation and fertilizers in fertility maintenance: Just how long an experiment should run to determine the true values of rotation and the use of fertilizers in maintaining productivity is difficult to state; probably 30 or 40 years would suffice. More carefully planned experiments seem necessary and advisable, to enable the gathering of more facts on a problem which is so intimately associated with the Nation's food-production problem.

Such a study of crop rotation and the use of fertilizers from the points of view of maintaining and increasing soil fertility gives added value to all long-time experiments involving continuous-culture plots.

To return to the first question proposed, concerning the comparative effects of rotation and the use of fertilizer on crop yields:

The soil of the three named Rothamsted fields consists of "'rather a heavy loam resting upon chalk.' * * * Notwithstanding the irregularity of the subsoil, the agricultural character of the soil is fairly uniform all over the estate; some fields work rather more heavily than others, and the proportion of stones lying on the surface varies somewhat, but these differences are comparatively unimportant. The soil passes into the subsoil without any sharp line of distinction, and the distribution of flints in the subsoil is very irregular, while the solid chalk is reached at depths varying between 8 and 12 feet.

"In the Rothamsted arable soils * * * there has always been sufficient carbonate of lime to keep up a neutral condition and put out of action any acid as fast as it was produced. However, it was observed later that one of the Rothamsted fields did contain plots on which the soil had become acid through the application of ammonium salts year after year for a long period; this was the Park grass field, which is cut for hay every year," a field not included in this study (*4, pp. 24, 25, 292, 293*).

The Rothamsted soil is very old, agriculturally. In 1881 Sir John Lawes said of it: "At what period my land was first brought into arable cultivation it is impossible to say, but at Rothamsted I have records which prove that wheat and other corn crops (meaning small grains) were grown 250 years ago upon these same fields which are now under experiment; there are, however, no data to show how often a field was cropped in succession." (*8, p. 12.*)

EXPERIMENTAL DATA

The data presented in Table 2 show the comparative effects of crop rotation and the use of fertilizers on the average yields of wheat and barley for a period of 72 years on the old arable soil at Rothamsted, when rotation and the use of fertilizer are practiced independently of each other. The first wheat yield in rotation on the Agdell field was obtained in the year 1851, and other yields were obtained every fourth year up to and including 1919. This gives a record of 18 crops of wheat grown in rotation, the average yield of which is compared with the average yields obtained in the same years on nine different plots on the Broadbalk field where wheat is grown in continuous culture. Each of the latter averages, therefore, represents 18 yields obtained during the same years that wheat has been grown on the rotation plots.

Since the experiments with barley in continuous culture were not begun until 1852, the first comparable yields of this crop were obtained in 1853, the second year of barley in rotation. Comparisons in average yields of barley are made in a similar manner as in case of the wheat. Thus each of the average yields of barley on the Hoos field represents 18 crops which were grown during the same years in which barley has been grown in rotation.

In the last two columns are given the increases in yields of both wheat and barley over the respective check plots in continuous culture. These gains express the absolute values of crop rotation and the use of fertilizers in effecting differences in yields on these particular plots.

TABLE 2.—*Comparative effects of crop rotation and the use of fertilizers on the yields of wheat and barley at Rothamsted* (*15*)

[Crop rotation and the use of fertilizer acting apart from each other]

Field and plot No.	Crop	Soil treatment (fertilizers given in pounds per acre annually)	Average yield per acre (18 crops) [1]	Increase due to rotation	Increase due to fertilizers
			Bushels [2]	*Bushels*	*Bushels*
Agdell, rotation field 6–O.	Wheat	Check plot, no fertilizer—rotation only	24.05	[3] 11.72	----------
Broadbalk, continuous culture:					
3	do	Check plot, no fertilizer	12.33	----------	----------
10_a	do	400 pounds ammonium salts [4] (86 pounds N, or 2N).	19.35	----------	7.02
11	do	400 pounds ammonium salts, 392 pounds superphosphate (2N, P).	22.62	----------	10.29
5	do	792 pounds minerals,[5] no nitrogen (P, K)	15.00	----------	2.67
6	do	Minerals and 200 pounds ammonium salts (N, P, K).	23.58	----------	11.25
7	do	Minerals and 400 pounds ammonium salts (2N, P, K).	32.20	----------	19.87
8	do	Minerals and 600 pounds ammonium salts (3N, P, K).	36.68	----------	24.35
9_a	do	Minerals and 550 pounds nitrate of soda (2N, P, K).	32.01	----------	19.68
2_a	do	14 tons farm manure	34.90	----------	22.57
Agdell, rotation field 6–O.	Barley	Check plot, no fertilizer—rotation only	21.81	[3] 7.75	----------
Hoos, continuous culture:					
1–O	do	Check plot, no fertilizer	14.06	----------	----------
1–A	do	200 pounds ammonium salts (43 pounds N).	24.87	----------	10.81
1–AA	do	275 pounds nitrate of soda (43 pounds N)	28.32	----------	14.26
2–O	do	392 pounds superphosphate (P)	20.38	----------	6.32
2–A	do	200 pounds ammonium salts, 392 pounds superphosphate (N, P).	37.98	----------	23.92
2–AA	do	275 pounds nitrate of soda, 392 pounds superphosphate (N, P).	43.80	----------	29.74
4–O	do	792 pounds minerals, no nitrogen (P, K)	21.38	----------	7.32
4–A	do	Minerals and 200 pounds ammonium salts (N, P, K).	41.89	----------	27.83
4–AA	do	Minerals and 275 pounds nitrate of soda (N, P, K).	43.51	----------	29.45
7–2	do	14 tons farm manure	48.04	----------	33.98

[1] The 18 crops of wheat or barley in continuous culture correspond to the 18 wheat or barley years in rotation.
[2] Winchester or American bushels. One imperial or English bushel equals 1.032 American bushels.
[3] Difference in yield between check plots in rotation and in continuous culture.
[4] In each case ammonium salts include equal parts of sulphate and chloride.
[5] In each case minerals include 392 pounds of superphosphate, 200 pounds of sulphate of potash, 100 pounds sodium sulphate, and 100 pounds of magnesium sulphate.

In case of the wheat, it is to be observed that rotation effected a larger increase in yields than the following annual applications of chemical fertilizers in continuous culture: 400 pounds of ammonium salts; 792 pounds of a mixture of ammonium salts and superphosphate; 792 pounds of mineral salts containing both phosphate and potash; and a mixture of chemicals containing, in addition to sodium and magnesium sulphates, 200 pounds of ammonium salts, 392 pounds of superphosphate, and 200 pounds of sulphate of potash. The effectiveness of the fertilizer applications made on plots numbered 7, 8, 9_a and 2_a (Broadbalk field) is, in each case, greater than that of rotation.

This greater effect, however, has little or no meaning from the point of view of practical farming, since these fertilizer applications are so at variance with modern fertilizer practices. Even an annual acre application similar to that made on plot 6 may be regarded as excessive; if not excessive, certainly uneconomical.

The value of rotation in maintaining the barley yields is greater than that of 392 pounds of superphosphate, in continuous culture, or of a mixture of chemicals containing 392 pounds of superphosphate and 200 pounds of sulphate of potash. In comparing plots 4–A, Hoos field, and No. 6, Broadbalk field, it appears that this particular fertilizer treatment is much more effective on barley than on wheat.

Of the different fertilizer treatments indicated in Table 2, only two can be considered in further study: No. 6 on the Broadbalk field and 4–A on the Hoos field, since the treatments on these plots come nearest to being comparable with those on the fertilized plot 2–C, Agdell field.

ROTATION AND THE USE OF FERTILIZERS CONJOINED

In order to compare the effects of rotation and the use of fertilizer when practiced independently of each other with their effects when these practices are conjoined, it is necessary that the same kind and quantity of fertilizer be used per acre on a crop in rotation as when it is grown in continuous culture. On the rotation plots on the Agdell field, plot No. 2 in series C receives the same kind of fertilizer salts as plots No. 6 on the Broadbalk field and 4–A on the Hoos field. The quantity applied per acre in each case, however, is not the same for the rotation period. Nevertheless, these are the best comparisons possible on the Rothamsted fields.

In Table 3 are shown the kinds and quantities of fertilizer materials that are applied on the three plots under consideration.

TABLE 3.—*Fertilizers applied on three plots at Rothamsted*

Field and plot No.	Crop	Pounds of fertilizer salts applied per acre					Total per acre for each rotation period (pounds)
		Ammonium[1] salts	Superphosphate	Sulphate of potash	Sodium sulphate	Magnesium sulphate	
Agdell 2–C	Rutabagas	200	392	500	100	200	1,392
	Barley						
	Legumes						
	Wheat						
Hoos 4–A	Barley[2]	200	392	200	100	100	3 968
Broadbalk 6	Wheat[2]	200	392	200	100	100	3,968

[1] Equal parts of ammonium sulphate and ammonium chloride.
[2] Continuous culture, fertilizers applied annually.

It is to be observed that nearly three times as much fertilizer is used per acre on the plots in continuous culture per rotation period as on the plot in rotation. Furthermore, on the Agdell field no direct application of fertilizer is made to either wheat or barley in the rotation. Barley thus receives the residual effects of the fertilizer one year after its application in the rotation, and wheat receives these effects three years after. These points must be kept in mind when the following results are considered.

In Table 4 are presented the yields of wheat on the Broadbalk and Agdell fields for each year that wheat has been grown in rotation on the latter field. In Table 5 are given similar data for barley. These results are here given in detail so as to form the basis for further study.

TABLE 4.—*Yields of wheat grown in continuous culture and in rotation, Rothamsted*

[Yields in Winchester or American bushels]

Years	Yields per acre on the Broadbalk field, continuous culture		Yields per acre on the Agdell field, rotation	
	Unfertilized plot 3	Fertilized plot 6	Unfertilized plot 6–O	Fertilized plot 2–C
	Bushels	*Bushels*	*Bushels*	*Bushels*
1851	16.38	33.22	29.41	29.80
1855	17.54	28.90	36.38	38.57
1859	18.96	30.81	36.38	41.02
1863	17.80	40.89	35.22	47.60
1867	9.16	16.25	21.67	24.51
1871	9.68	17.54	21.29	24.76
1875	8.90	16.80	22.32	32.90
1879	4.90	10.84	10.71	13.42
1883	14.32	28.51	30.32	46.57
1887	15.35	24.00	26.45	43.60
1891	14.19	26.96	30.44	45.80
1895	10.32	21.80	23.99	40.25
1899	12.38	19.35	31.22	44.25
1903	7.84	18.37	19.74	29.15
1907	9.39	24.67	22.08	30.24
1911	12.90	17.75	25.28	39.22
1915	12.49	27.55	6.50	10.84
1919	9.49	20.12	3.51	2.27
Average (18 crops)	12.33	23.58	24.05	32.49

TABLE 5.—*Yields of barley grown in continuous culture and in rotation, Rothamsted*

[Yields in Winchester or American bushels]

Years	Yields per acre on the Hoos field, continuous culture		Yields per acre on the Agdell field, rotation	
	Unfertilized plot 1–O	Fertilized plot 4–A	Unfertilized plot 6–O	Fertilized plot 2–C
	Bushels	*Bushels*	*Bushels*	*Bushels*
1853	26.57	39.47	35.48	39.47
1857	26.96	59.22	50.05	49.54
1861	16.77	56.38	39.86	62.57
1865	18.58	47.99	40.25	49.02
1869	15.74	50.83	25.41	44.25
1873	14.45	48.38	24.25	32.77
1877	17.67	52.12	24.25	35.86
1881	18.45	43.98	27.61	36.51
1885	9.55	33.02	12.51	35.86
1889	11.61	36.89	11.35	27.48
1893	8.41	31.73	17.42	20.90
1897	5.20	31.48	11.87	31.22
1901	5.20	25.54	23.99	27.09
1905	6.71	36.64	7.53	32.41
1909	13.42	45.72	10.32	34.47
1913	21.78	65.64	25.39	33.54
1917	8.15	17.75	2.58	15.48
1921	7.84	31.27	2.48	26.52
Average (18 crops)	14.06	41.89	21.81	35.27

The results of a study of the averages of these wheat and barley yields obtained at Rothamsted are summarized in Tables 6 and 7.

TABLE 6.—*Effects of crop rotation and the use of fertilizers on the yields of wheat and barley at Rothamsted*

[Rotation and fertilization practiced separately]

Crop and cultural conditions	Average yield per acre	Increase over check plot in continuous culture (c)	Relative value of crop rotation as compared with fertilizer in effecting larger yields [1]
	Bushels	*Bushels*	*Per cent*
Wheat:			
Rotation without fertilization (r) [2]	24.05	11.72	104.2
Use of fertilizer without rotation (f) [3]	23.58	11.25	----------
Barley:			
Rotation without fertilization (r)	21.81	7.75	27.8
Use of fertilizer without rotation (f)	41.89	27.83	----------

[1] Relative value of rotation obtained by dividing the increase from rotation (r) by the increase from the use of fertilizer (f).
[2] Small r indicates the effect of rotation when practiced independently of fertilization.
[3] Small f indicates the effect of fertilization when practiced in the absence of rotation.

It is to be observed that, in case of wheat, crop rotation without fertilization is 104.2 per cent as efficient as the use of chemical fertilizer without rotation in effecting increases over the check plot in continuous culture; whereas in case of barley, rotation is only 27.8 per cent as effective as the chemical fertilizer.

In Table 7 are shown the conjoint effects of crop rotation and the use of fertilizer. Under the caption heading of the fourth column are given the values of rotation (*R*) and the use of fertilizer (*F*). Capital *R* represents the average increase in crop yield that was effected by adding rotation to cultivation and the use of fertilizer, as derived from the formula *cfr* – *cf;* and capital *F* represents the average increase that resulted when to cultivation and rotation was conjoined the use of fertilizer, as derived from the formula *cfr* – *cr*.

In the fifth column are given the relative values for *R*, as obtained in each case by dividing the absolute value for *R* by the absolute value for *F*.

In the last two subcolumns are compared the sum of the increases effected by rotation and fertilization when practiced independently of each other and the actual increase effected when the two practices are combined.

TABLE 7.—*Relative values of rotation and additive effects of rotation and the use of fertilizers when the two practices are combined*

[Rothamsted, results of 72 years]

Crop	Cultural conditions	Average yield per acre	Values of *R* and *F* [1]		Relative value of *R* [2]	Additive effects of rotation and fertilization	
			R	*F*		Sum of increases effected by rotation and fertilization when practiced separately (r+f)	Actual increase effected by conjoining rotation and fertilization
		Bushels	*Bushels*	*Bushels*	*Per cent*	*Bushels*	*Bushels*
Wheat	Rotation and use of fertilizer	32.49	8.91	8.44	105.6	22.97	20.16
Barley	do	35.27	−6.62	13.46	−49.2	35.58	21.21

[1] Capital *R* indicates increase effected by adding rotation to fertilization. Capital *F* indicates increase effected by adding fertilization to rotation.
[2] Relative value of *R* as *R*:*F*, or *R*÷*F*.

It is to be observed that the increase (*R*) effected in the yield of wheat by adding rotation to the use of fertilizer is about equal to the increase (*F*) effected when the use of chemical fertilizer is combined with the practice of rotation. This is indicated by the relative value of 105.6 per cent for *R*. In case of barley, *R* has an absolute negative value of −6.62 bushels, or a negative relative value of −49.2 per cent. These negative values for *R* may be explained, at least in part, by the fact that the fertilizer treatments given to barley in rotation and continuous culture are not exactly comparable, since no fertilizer is applied directly to the barley crop in rotation, whereas in continuous culture a liberal direct application is made annually. (See Table 3.)

Combining the rotation and fertilization practices effected a total increase over the check plot in continuous culture, of 20.16 bushels of wheat, which increase is greater than the gain resulting from either rotation or the use of fertilizer alone. This fact defines and illustrates the meaning of the expression "additive effects of rotation and the use of fertilizers" as it is used in this bulletin. This definition is in harmony with the meaning "tending to increase." That is to say, the yield of wheat, for example, is increased when to rotation is added the use of fertilizers, or when to the use of fertilizers is conjoined rotation.

Three possibilities may result from conjoining the practices of rotation and of fertilization: The total increase resulting may be equal to, less than, or greater than the sum of the increases effected by rotation and fertilization when practiced independently of each other. In describing these additive effects the following expressions are used: "Fully additive," "less than fully additive," and "more than fully additive," respectively. The data in Table 7 show that, on wheat, the effects produced in conjoining rotation and the use of chemical fertilizer are somewhat less than fully additive; while in case of barley, the combined effects are not additive, reflecting, no doubt, the difference in fertilizer treatments and the different habits of the barley plant as compared with wheat.

In discussing the yields of barley grown in continuous culture, Lawes and Gilbert stated that results, as compared with wheat, were dependent on the differences in the habits of the two plants. Wheat, because of its greater root system, gains possession of a much greater range of soil, especially in depth, than barley; barley, on the other hand, is a surface feeder and hence relies in a much greater degree on the nutrients within the soil near the surface. Accordingly, barley is found to be more benefited by direct applications of fertilizers than is wheat when sown under equal soil conditions (*9, p. 100*).

DIAGRAMMATIC SUMMARY OF ROTHAMSTED RESULTS

Figure 2 represents in diagrammatic form the average wheat and barley yields that have been obtained on the four Rothamsted plots herein considered, summarizing the following points: The portion of each yield (in bushels) that is credited to cultivation alone (*c*), that is, the yield obtained in continuous culture without fertilizers; the increase effected by combining rotation or the use of chemical fertilizer with cultivation; and the total increase effected, over cultivation alone, by conjoining rotation and the use of fertilizer.

The third bar in each of the series of results shown in the chart is the most interesting. The total gain above the check plot in continuous culture, as indicated in each series, is the actual increase effected when to cultivation are added the conjoint effects of rotation and fertilization. Here no assumptions are involved.

When to rotation is added the practice of fertilization, the actual increase obtained in the yield of wheat is 8.44 bushels. This increase, which may be indicated by capital *F*, is shown by the diagonal hachure at the top portion of the bar. On the other hand, when to fertilization is added rotation, the increase effected is 8.91 bushels, which increase may be indicated by capital *R*, and is shown by the diagonal hachure below the figure, 20.16, indicating the total gain. The unhachured portion of the bar represents 2.81 bushels, being a part of the total gain; but there is no way to determine just how much of this undivided gain should be credited to rotation and to the use of fertilizers. This undivided increase measures the interactive effects of rotation and the use of fertilizers when these two practices are conjoined. These effects may be interpreted in three ways: (1) When, under the conditions of these fertility experiments on wheat, rotation of crops and the use of fertilization are conjoined, the effectiveness of rotation, as determined when rotation is practiced in the absence of fertilizers, is reduced and the efficiency of the fertilizer remains the same as when it acts apart from rotation; or (2) the effect of crop rotation remains the same and the effectiveness of the use of fertilizers is diminished; or (3) it may mean that the efficiency of both rotation and the use of fertilizers is diminished in the same or in different degrees.

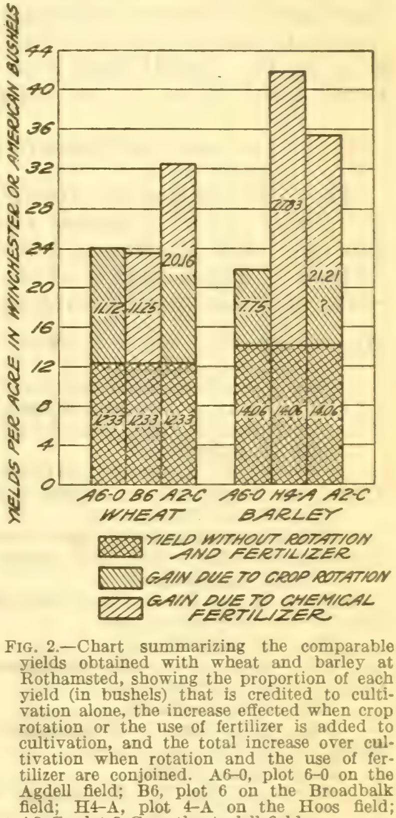

FIG. 2.—Chart summarizing the comparable yields obtained with wheat and barley at Rothamsted, showing the proportion of each yield (in bushels) that is credited to cultivation alone, the increase effected when crop rotation or the use of fertilizer is added to cultivation, and the total increase over cultivation when rotation and the use of fertilizer are conjoined. A6–0, plot 6–0 on the Agdell field; B6, plot 6 on the Broadbalk field; H4–A, plot 4–A on the Hoos field; A2–C, plot 2–C on the Agdell field

The unallocated value as shown by the unhachured portion also shows the difference (2.81 bushels) between the sum of the increases effected by rotation and the use of fertilizers when acting independently of each other and the actual increase obtained as a result of their combined effects, but just how much should be subtracted from the separate gains effected by rotation and the use of fertilizers can not be determined.

In case of barley, *R* has a negative value of −6.62 bushels, due probably to the fertilizer treatments not being exactly comparable. Whether or not rotation would have effected any increase at all if conjoined with fertilization under more comparable conditions remains a question. Nevertheless, the division of the third bar in the barley series illustrates the actual results obtained under the conditions of the experiment: Cultivation alone gave an average yield of 14.06 bushels; combining rotation with cultivation effected an increase of 7.75 bushels; and combining fertilization with cultivation and rotation resulted in an additional increase of 13.46 bushels. This seems to be the more reasonable and practical interpretation of these results, especially since the conjoint action of rotation and fertilization effecting the total increase of 21.21 bushels over cultivation alone involves the fertilizer treatment made in rotation on the Agdell field and not the annual application made in continuous culture on the Hoos field.

COLUMBIA EXPERIMENTS WITH WHEAT, CORN, AND OATS

The long-continued experiments at Columbia, Mo., were begun in 1888 (*11*). Comparable yields suitable for this study begin with the year 1889 for wheat, 1890 for corn, 1891 for oats and 1896 for timothy. These experiments now include 39 one-fourteenth-acre plots, of which the following are herein considered:

Six-year rotation, corn, oats, wheat, clover, timothy, and timothy:
- Plot 13, unfertilized.
- Plot 3, fertilized with chemical fertilizers.
- Plots 11, 12, 14, 19 and 20, fertilized with farm manure.

Four-year rotation, corn, oats, wheat and clover:
- Plot 39, unfertilized.
- Plots 34, 35, 37 and 38, fertilized with farm manure.

Three-year rotation, corn, wheat and clover:
- Plot 27, unfertilized.
- Plot 28, fertilized with farm manure.

Two-year rotation, wheat and clover.
- Plot 33, unfertilized.
- Plots 31 and 32, fertilized with farm manure.

Corn in continuous culture.
- Plot 17, unfertilized.
- Plot 18, fertilized with farm manure.

Oats in continuous culture:
- Plot 16, unfertilized.
- Plot 15, fertilized with farm manure.

Wheat in continuous culture:
- Plot 9, unfertilized.
- Plot 2, fertilized with chemical fertilizer.
- Plots 5, 10, 21, 24, 30 and 36, fertilized with farm manure.

Timothy in continuous culture:
- Plot 23, unfertilized.
- Plot 22, fertilized with farm manure.

As in case of the Rothamsted experiments, no provision has been made for a replication of the plots representing the different rotations. For this reason, unfortunately, the effectiveness of the four rotations can not be compared, since, for example, the average yield of corn in one rotation represents a different combination of seasonal effects than the average yield in another rotation. However, in all the systems of cropping the effect of rotation on crop yields may be compared with the effectiveness of the use of farm manure, and, in case of wheat in the 6-year rotation, with the use of a complete chemical fertilizer.

The soil on which the Missouri experiments are conducted is designated as Putnam silt loam. It is described as a dark brownish gray soil "9 to 12 inches deep, grading into a grayish subsurface layer 4 to 6 inches thick." Below this there is another gradation into a brown, heavy clay loam, rather impervious in character. At depths from 13 to 18 inches the soil is a yellowish-gray, silty clay loam, more friable than the layer above it. "The surface drainage is generally good. * * * The soil of the field is * * * fairly uniform in fertility." As a rule, Putnam silt loam is in need of lime (*10, p. 5*). The Missouri experimental results herein presented have been obtained on an unlimed soil.

EXPERIMENTAL DATA

Since, in these particular experiments, the different fertilizer treatments in continuous culture are the same as those in rotation, it seemed best, at the outset, to present in detail all the data on which this study of the Missouri experiments is based. The data are given in several tables, each table containing comparable yields of a particular crop grown both in rotation and in continuous culture. In Table 8, for example, are given the yields of corn obtained on the unfertilized and manured plots for each year that it has been grown in the 6-year rotation, up to, and including, 1916. In the other portion of the same table are given the yields on similarly treated plots in continuous culture for each year that corn has been grown in the rotation.

SIX-YEAR ROTATION AND CONTINUOUS CULTURE

TABLE 8.—*Comparable yields of corn in the 6-year rotation and in continuous culture, Missouri*

[Yields in bushels per acre]

Year	6-year rotation (corn, oats, wheat, clover, timothy, timothy)					Continuous culture	
	No fertilizer, plot 13	Farm manure [1]				No fertilizer, plot 17	Farm manure,[1] plot 18
		Plot 11	Plot 14	Plot 20	Average or summary		
1892	25.7	37.9			37.9	42.1	51.4
1898	25.1	27.0			27.0	23.9	25.6
1903	85.4			78.7	78.7	29.5	55.5
1904	54.2	43.8			43.8	17.1	13.4
1910	39.4	51.6	52.9		52.3	1.9	6.5
1916	19.0			28.0	28.0	7.4	14.6
6-year average	41.5				44.6	20.3	27.8

[1] The mean application of manure in all cases is 6.8 tons per acre annually, in both rotation and continuous culture.

TABLE 9.—*Comparable yields of oats in the 6-year rotation and in continuous culture, Missouri*

[Yields in bushels per acre]

Year	6-year rotation (corn, oats, wheat, clover, timothy, timothy)							Continuous culture	
	No fertilizer, plot 13	Farm manure						No fertilizer, plot 16	Farm manure, plot 15
		Plot 11	Plot 12	Plot 14	Plot 19	Plot 20	Average or summary		
1893	21.9	27.8	----	----	----	----	27.8	17.8	30.6
1899	32.8	36.7	----	----	----	----	36.7	13.4	27.3
1905	16.7	28.0	----	----	----	----	28.0	7.3	19.1
1911	13.8	18.5	17.4	24.0	22.5	17.9	20.1	5.0	26.1
1917	51.1	----	----	----	----	60.5	60.5	53.7	65.1
5-year average	27.3	----	----	----	----	----	34.6	19.5	33.6

TABLE 10.—*Comparable yields of wheat in the 6-year rotation and in continuous culture, Missouri*

[Yields in bushels per acre]

Year	6-year rotation (corn, oats, wheat, clover, timothy, timothy)							Continuous culture								
	No fertilizer, plot 13	Chemical fertilizer,[1] plot 3	Farm manure					No fertilizer, plot 9	Chemical fertilizer,[1] plot 2	Farm manure						
			Plot 11	Plot 12	Plot 14	Plot 20	Average or summary			Plot 5	Plot 10	Plot 21	Plot 24	Plot 30	Plot 36	Average or summary
1889	6.5	17.7	16.2	----	----	----	16.2	8.2	20.6	8.1	15.0	11.8	17.0	20.9	23.0	16.0
1895	33.0	38.7	44.0	----	----	----	44.0	22.0	39.3	34.3	40.7	43.3	39.2	41.3	33.0	38.6
1901	39.3	43.3	43.3	----	----	----	43.3	15.6	28.7	23.3	25.2	24.1	23.6	28.5	27.2	25.3
1907	10.8	24.1	26.4	----	----	----	26.4	7.1	27.9	17.1	10.8	24.1	23.1	11.4	24.8	18.6
1912	14.0	22.0	22.5	23.3	22.0	16.1	21.0	1.3	7.7	12.6	12.5	12.1	10.7	12.0	10.0	11.7
1918	16.8	34.2	----	----	----	34.3	34.3	21.0	34.3	----	30.3	----	----	----	----	30.3
6-year average	20.1	30.0	----	----	----	----	30.9	12.5	26.4	----	----	----	----	----	----	23.4

[1] The annual application of complete chemical fertilizer for wheat on plots 2 and 3 are the same. (See Table 22.)

TABLE 11.—*Comparable yields of timothy in the 6-year rotation and in continuous culture, Missouri*

[Yields in pounds per acre]

Year	6-year rotation (corn, oats, wheat, clover, timothy, timothy)						Continuous culture	
	No fertilizer, plot 13	Farm manure					No fertilizer, plot 23	Farm manure, plot 22
		Plot 11	Plot 12	Plot 19	Plot 20	Average or summary		
1890	1,790	3,120	4,690	----	5,040	4,283	2,290	5,790
1891	3,920	6,860	----	----	----	6,860	4,760	7,600
1896	1,900	----	----	5,000	----	5,000	2,480	5,840
1897	4,600	6,700	----	----	----	6,700	2,400	6,100
1902	130	2,750	1,750	----	2,000	2,167	4,500	5,700
1908	3,536	7,398	7,840	----	7,240	7,493	3,650	7,812
1909	2,820	8,320	----	----	----	8,320	2,146	6,032
1914	124	----	----	----	766	766	546	889
1915	3,192	----	----	----	6,818	6,818	3,276	6,888
9-year average	2,446	----	----	----	----	5,379	2,894	5,850

FOUR-YEAR ROTATION AND CONTINUOUS CULTURE

TABLE 12.—*Comparable yields of corn in the 4-year rotation and in continuous culture, Missouri*

[Yields in bushels per acre]

Year	4-year rotation (corn, oats, wheat, clover)						Continuous culture	
	No fertilizer, plot 39	Farm manure					No fertilizer, plot 17	Farm manure, plot 18
		Plot 34	Plot 35	Plot 37	Plot 38	Average or summary		
1890	35.3				50.9	50.9	41.1	60.7
1894	34.3				34.0	34.0	17.1	30.3
1898	28.2				31.7	31.7	23.9	25.6
1902	54.0			80.7	78.5	79.6	38.0	79.4
1906								
1911	29.9		37.3	31.8	33.8	34.3	13.2	25.1
1915	49.6	55.6				55.6	38.0	45.7
6-year average	38.6					47.7	28.6	44.5

TABLE 13.—*Comparable yields of oats in the 4-year rotation and in continuous culture, Missouri*

[Yields in bushels per acre]

Year	4-year rotation (corn, oats, wheat, clover)						Continuous culture	
	No fertilizer, plot 39	Farm manure					No fertilizer, plot 16	Farm manure, plot 15
		Plot 34	Plot 35	Plot 37	Plot 38	Average or summary		
1891	21.6				29.7	29.7	18.4	25.9
1895	31.6				40.6	40.6	28.1	42.2
1899	26.3				32.2	32.2	13.4	27.3
1903								
1907	26.8				37.8	37.8	21.9	37.4
1912	30.3	40.8	51.6	53.8	14.4	40.2	29.3	32.4
1916	30.6	42.9				42.9	29.0	30.2
6-year average	27.9					37.2	23.4	32.6

TABLE 14.—*Comparable yields of wheat in the 4-year rotation and in continuous culture, Missouri*

[Yields in bushels per acre]

Year	4-year rotation (corn, oats, wheat, clover)						Continuous culture							
	No fertilizer, plot 39	Farm manure					No fertilizer, plot 9	Farm manure						
		Plot 34	Plot 35	Plot 37	Plot 38	Average or summary		Plot 5	Plot 10	Plot 21	Plot 24	Plot 30	Plot 36	Average or summary
1889	25.8				26.9	26.9	8.2	8.1	15.0	11.8	17.0	20.9	23.0	16.0
1893	14.0				15.2	15.2	0						4.0	4.0
1897	28.7				37.3	37.3	1.7	13.8	6.1	8.4	8.2	14.8	14.7	11.0
1901	34.0				37.2	37.2	15.6	23.3	25.2	24.1	23.6	28.5	27.2	25.3
1905	20.8				31.8	31.8		12.4	15.4	15.6	15.6	29.7		17.7
1909	21.7				15.7	15.7	0		15.2	11.7	13.8	10.4	21.9	14.6
1913	13.8	28.3	25.1	24.9	27.8	26.5	8.8	15.9	16.9	17.4	17.3	22.5	20.9	18.5
1917	30.0	39.4				39.4	0.2		10.9					10.9
8-year average	23.6					28.8	4.9							14.8

THREE-YEAR ROTATION AND CONTINUOUS CULTURE

TABLE 15.—*Comparable yields of corn and wheat in the 3-year rotation and in continuous culture, Missouri*

[Yields in bushels per acre]

Year	Corn				Year	Wheat			
	3-year rotation (corn, wheat, clover)		Continuous culture			3-year rotation (corn, wheat, clover)		Continuous culture	
	No fertilizer, plot 27	Farm manure, plot 28	No fertilizer, plot 17	Farm manure, plot 18		No fertilizer, plot 27	Farm manure, plot 28	No fertilizer, plot 9	Farm manure, average of 6 plots[1]
1890	28.4	45.8	41.1	60.7	1889	14.9	18.4	8.2	16.0
1893	24.3	34.6	24.9	34.0	1892	9.2	24.2	6.2	19.3
1896	34.9	51.4	21.0	46.4	1895	27.5	42.3	22.0	38.6
1899	25.5	37.9	19.4	31.9	1898	5.0	15.7	2.7	6.0
1902	65.3	88.6	38.0	79.4	1901	23.3	34.5	15.6	25.3
1905	50.7	77.6	11.9	64.3	1904	--------	--------	--------	--------
1907	47.2	65.9	11.7	33.4	1908	6.9	29.2	7.1	19.1
1910	16.6	32.7	1.9	6.5	1911	11.5	33.6	5.0	19.1
1913	13.9	24.7	7.0	19.2	1914	18.1	--------	20.1	26.4
1916	19.6	--------	7.4	14.6	1917	13.5	--------	0.2	10.9
Average	32.6	51.0	18.4	39.0	Average	14.4	28.3	9.7	20.1

[1] Average of plots 5, 10, 21, 24, 30, and 36, continuous culture.

TWO-YEAR ROTATION AND CONTINUOUS CULTURE

TABLE 16.—*Comparable yields of wheat in the 2-year rotation and in continuous culture, Missouri*

[Yields in bushels per acre]

Year	2-year rotation (wheat and clover)		Continuous culture							
				Farm manure						
	No fertilizer, plot 33	Farm manure, plot 31	No fertilizer, plot 9	Plot 5	Plot 10	Plot 21	Plot 24	Plot 30	Plot 36	Average or summary
889	23.7	21.3	8.2	8.1	15.0	11.8	17.0	20.9	23.0	16.0
891	33.3	31.4	24.6	27.2	31.3	30.8	30.6	31.9	27.3	29.9
893	8.3	9.3	--------	--------	--------	--------	--------	--------	4.0	4.0
895	34.7	43.3	22.0	34.3	40.7	43.3	39.2	41.3	33.0	38.6
897	12.5	30.3	1.7	13.8	6.1	8.4	8.2	14.8	14.7	11.0
899	2.7	14.8	2.7	13.6	15.8	15.8	12.0	15.7	18.2	15.2
01	30.9	38.2	15.6	23.3	25.2	24.1	23.6	28.5	27.2	25.3
03	--------	--------	11.5	17.3	16.0	6.8	7.5	7.4	--------	11.0
05	10.0	11.1	--------	12.4	15.4	15.6	15.6	29.7	--------	17.7
07	12.8	24.2	7.1	17.1	10.8	24.1	23.1	11.4	24.8	18.6
1909	14.3	12.1	--------	--------	15.2	11.7	13.8	10.4	21.9	14.6
1911	16.9	32.6	5.0	6.5	10.3	30.6	28.6	18.4	20.3	19.1
1913	25.7	27.8	8.8	15.9	16.9	17.4	17.3	22.5	20.9	18.5
1915	11.7	25.1	2.0	--------	18.7	--------	--------	--------	--------	18.7
17	20.7	27.4	0.2	--------	10.9	--------	--------	--------	--------	10.9
Average	18.4	24.9	9.1	--------	--------	--------	--------	--------	--------	17.9

Inasmuch as the efficiencies of the four Missouri rotations, as determined by comparing the average yields of the crops in common, are not comparable, because of the fact that the average yields of the crops of one rotation represent different seasonal effects than those of another, the effects of rotation and the use of manure on the yields of each crop in the various rotations, as measured in terms of crop increases, are simply averaged. Thus, from the foregoing experimental data the average yields of each crop in continuous culture and in the different rotations are first selected and arranged in table form, a table for each crop; then from these yields are calculated the increases effected by rotation and fertilization; and each of these sets of values, in turn, are averaged. The general averages thus obtained for a given crop express truer absolute values of rotation and fertilizers, particularly of manure, because such averages include different combinations of crops and seasonal effects.

Two groups of observations are made: (1) A comparison of the effects of crop rotation and fertilization when they are practiced independently of each other; and (2) a comparison of the effects when rotation and fertilization are conjoined.

ROTATION AND FERTILIZATION PRACTICED INDEPENDENTLY

In Tables 17, 18, 19, and 20 are summarized, from the foregoing tables, those average yields of wheat, corn, oats, and timothy from which are determined the effects of both rotation and the use of fertilizers on crop yields when practiced independently of each other. In the columns to the right of the one containing the average yields are given the increases in yield (over the check plots in continuous culture) owing to crop rotation, the use of farm manure, and chemical fertilizers, respectively. At the bottom of each table are given, in terms of bushels of increase, the average absolute values of crop rotation and the use of farm manure, and, in case of wheat, an additional single comparison of absolute values of rotation and the use of chemical fertilizers.

TABLE 17.—*The effects of rotation and of fertilization on the yields of wheat, showing increases over cultivation alone*

[Rotation and fertilization practiced independently of each other]

Plot No.	Cultural conditions	Average yield per acre	Average increase due to rotation	Average increase due to use of manure	Average increase due to use of chemical fertilizer
	6-year rotation and continuous culture:				
13	Rotation without use of chemical fertilizer	*Bushels* 20.1	*Bushels* 7.6	*Bushels*	*Bushels*
2	Use of chemical fertilizer without rotation	26.4			13.9
5, 10, 21, 24, 30, 36	Use of manure without rotation	23.4		10.9	
9	No manure and no rotation	12.5			
	4-year rotation and continuous culture:				
39	Rotation without the use of manure	23.6	18.7		
5, 10, 21, 24, 30, 36	Use of manure without rotation	14.8		9.9	
9	No manure and no rotation	4.9			
	3-year rotation and continuous culture:				
27	Rotation without use of manure	14.4	4.7		
5, 10, 21, 24, 30, 36	Use of manure without rotation	20.1		10.4	
9	No manure and no rotation	9.7			
	2-year rotation and continuous culture:				
33	Rotation without use of manure	18.4	9.3		
5, 10, 21, 24, 30, 36	Use of manure without rotation	17.9		8.8	
9	No manure and no rotation	9.1			
	Average increase from rotation and use of manure		10.1	10.0	
	Increase from rotation and use of chemical fertilizer		7.6		13.9

TABLE 18.—*Effects of crop rotation and of the use of farm manure on the yields of corn*

[Rotation and the use of manure practiced independently of each other]

Plot No.	Cultural conditions	Average yield per acre	Average increase due to rotation	Average increase due to use of manure
	6-year rotation and continuous culture:	*Bushels*	*Bushels*	*Bushels*
13	Rotation without use of manure	41.5	21.2	
18	Use of manure without rotation	27.8		7.5
17	No manure and no rotation	20.3		
	4-year rotation and continuous culture:			
39	Rotation without use of manure	38.6	10.0	
18	Use of manure without rotation	44.5		15.9
17	No manure and no rotation	28.6		
	3-year rotation and continuous culture:			
27	Rotation without use of manure	32.6	14.2	
18	Use of manure without rotation	39.0		20.6
17	No manure and no rotation	18.4		
	Average increase from rotation and use of manure		15.1	14.7

TABLE 19.—*Effects of crop rotation and of the use of farm manure on the yields of oats*

[Rotation and the use of manure practiced independently of each other]

Plot No.	Cultural conditions	Average yield per acre	Average increase due to rotation	Average increase due to use of manure
	6-year rotation and continuous culture:	*Bushels*	*Bushels*	*Bushels*
13	Rotation without use of manure	27.3	7.8	
15	Use of manure without rotation	33.6		14.1
16	No manure and no rotation	19.5		
	4-year rotation and continuous culture:			
39	Rotation without use of manure	27.9	4.5	
15	Use of manure without rotation	32.6		9.2
16	No manure and no rotation	23.4		
	Average increase from rotation and use of manure		6.2	11.7

TABLE 20.—*Effects of crop rotation and of the use of farm manure on the yields of timothy*

[Rotation and the use of manure practiced independently of each other]

Plot No.	Cultural conditions	Average yield per acre	Average increase due to rotation	Average increase due to use of manure
	6-year rotation and continuous culture:	*Pounds*	*Pounds*	*Pounds*
13	Rotation without use of manure	2,446	−448	
22	Use of manure without rotation	5,850		2,956
23	No manure and no rotation	2,894		

In Table 21 are summarized the data contained in the four foregoing tables. Timothy is not included, since results seem to show that this crop is not benefited by rotation under conditions of these experiments.

TABLE 21.—*Effects of crop rotation and of the use of fertilizers on the yields of wheat, corn, and oats at Columbia, Mo.*

[Rotation and fertilization practiced separately]

Crop	Cultural conditions	Average yield per acre	Average increase over check plot in continuous culture (c)	Relative value of crop rotation, as compared with fertilizers, in effecting larger yields
		Bushels	*Bushels*	*Per cent*
Wheat	Crop rotation without use of manure (r)	19.1	10.0	100.0
	Use of manure without rotation (f)	19.1	10.0	
	Crop rotation without use of chemical fertilizer (r)	20.1	7.6	54.7
	Use of chemical fertilizer without rotation (f)	26.4	13.9	
Corn	Crop rotation without use of manure (r)	37.5	15.1	102.7
	Use of manure without rotation (f)	37.1	14.7	
Oats	Crop rotation without use of manure (r)	27.6	6.2	53.0
	Use of manure without rotation (f)	33.1	11.7	

These average results show that, under the conditions of the Missouri experiments, crop rotation without the use of manure is as effective in increasing the yields of wheat and corn, over the check plots in continuous culture, as a mean annual application of 6.8 tons of manure without rotation. In case of oats, rotation proved to be slightly more than half as efficient as the use of manure.

The 6-year rotation of corn, oats, wheat, clover, timothy, and timothy practiced without the use of any fertilizer, is 54.7 per cent as efficient in increasing the average yield of wheat over cultivation alone as an annual application of a chemical mixture consisting of 495 pounds of sodium nitrate, 209 pounds of acid phosphate and 111 pounds of muriate of potash. (See Table 22.)

ROTATION AND THE USE OF FERTILIZERS CONJOINED

Since, in the Missouri experiments, the same quantities of manure have been applied per acre annually on all the plots herein considered (mean application of 6.8 tons per acre), the results in Tables 17, 18, 19, and 20, showing the separate effects of rotation and the use of fertilizers, are comparable with the results showing the combined effect of these two practices. As regards the use of chemical fertilizers on wheat, the quantity that has been applied per acre in continuous culture for the 6-year period is 553 pounds less than the total quantity applied to the crops in the 6-year rotation. This is shown in Table 22.

TABLE 22.—*Application of chemical fertilizer in rotation and continuous culture, Missouri*

Plot number	Crop	Kind and quantity of fertilizer materials used (annually per acre)			Total quantities for 6-year period (per acre)		
		Sodium nitrate	Acid phosphate	Muriate of potash	Sodium nitrate	Acid phosphate	Muriate of potash
		Pounds	*Pounds*	*Pounds*	*Pounds*	*Pounds*	*Pounds*
2 (rotation)	Corn	764	301	136	3,336	1,206	901
	Oats	375	157	98			
	Wheat	495	209	111			
	Clover	774	245	216			
	Timothy	464	147	170			
	do	464	147	170			
3 (continuous culture)	Wheat	495	209	111	2,970	1,254	666

In Tables 23, 24, 25, and 26 are summarized from Tables 8 to 16, inclusive, those average yields of wheat, corn, oats, and timothy which show the average effects of crop rotation and the use of fertilizers on the yield of wheat, corn, oats, and timothy when these two farm practices are conjoined. In the column to the right of the one containing the average yields are given the average increases, over check plots in continuous culture, due to the conjoint effects of rotation and the use of manure, and in case of wheat, the conjoint effects of rotation and the use of chemical fertilizer.

TABLE 23.—*Average effects of the conjoint action of crop rotation and the use of fertilizers on the yields of wheat, Missouri*

Plot No.	Cultural conditions, rotation and check plot in continuous culture	Average yield per acre	Average increase over check plot in continuous culture, due to rotation and use of fertilizers
	6-year rotation:	*Bushels*	*Bushels*
11, 12, 14, 20	Rotation and use of manure	30.9	18.4
3	Rotation and use of chemical fertilizer	30.0	17.5
9	No rotation and no fertilizer	12.5	
	4-year rotation:		
34, 35, 37, 38	Rotation and use of manure	28.8	23.9
9	No rotation and no manure	4.9	
	3-year rotation:		
28	Rotation and use of manure	28.3	18.6
9	No rotation and no manure	9.7	
	2-year rotation:		
31	Rotation and use of manure	24.9	15.8
9	No rotation and no manure	9.1	
	Average yield and increase effected by rotation and use of manure	28.2	19.1
	Yield and increase effected by rotation and use of chemical fertilizer	30.0	17.5

TABLE 24.—*Average effects of the conjoint action of crop rotation and the use of farm manure on the yields of corn*

Plot No.	Cultural conditions, rotation and check plot in continuous culture	Average yield per acre	Average increase over check plot in continuous culture due to rotation and use of manure
	6-year rotation:	*Bushels*	*Bushels*
11, 14, 20	Rotation and use of manure	44.6	24.2
17	No rotation and no manure	20.3	
	4-year rotation:		
34, 35, 37, 38	Rotation and use of manure	47.7	19.1
17	No rotation and no manure	28.6	
	3-year rotation:		
28	Rotation and use of manure	51.0	32.6
17	No rotation and no manure	18.4	
	Average yield and increase effected by rotation and use of manure	47.7	25.3

TABLE 25.—*Average effects of the conjoint action of crop rotation and the use of manure on the yields of oats*

Plot No.	Cultural conditions, rotation and check plot in continuous culture	Average yield per acre	Average increase over check plot in continuous culture due to rotation and use of manure
		Bushels	*Bushels*
	6-year rotation:		
11, 12, 14, 19, 20	Rotation and use of manure	34.6	15.1
16	No rotation and no manure	19.5	
	4-year rotation:		
34, 35, 37, 38	Rotation and use of manure	37.2	13.8
16	No rotation and no manure	23.4	
	Average yield and increase effected by rotation and use of manure	35.9	14.5

TABLE 26.—*Average effects of the conjoint action of crop rotation and the use of manure on the yield of timothy*

Plot No.	Cultural conditions, rotation and check plot in continuous culture	Average yield per acre	Average increase over check plot in continuous culture due to rotation and use of manure
		Pounds	*Pounds*
	6-year rotation:		
11, 12, 19, 20	Rotation and use of manure	5,379	2,485
23	No rotation and no manure	2,894	

The average yields and increases given in Tables 21, 23, 24 and 25 are summarized in Table 27, in which are given the relative values of rotation (*R*) in effecting increases when conjoined with the use of fertilizers, and the additive effects of the conjoint action of rotation and the use of fertilizers on the yields of wheat, corn, and oats.

TABLE 27.—*Relative values of rotation (R) and additive effects on the yields of wheat, corn, and oats when rotation of crops and use of fertilizers are conjoined*

Crop	Cultural conditions	Average yield per acre	Values of *R* and *F*: *R*	Values of *R* and *F*: *F*	Relative value of *R*[1]	Additive effects of rotation and use of fertilizer: Sum of increases effected by rotation and use of fertilizer when practiced separately (*r*+*f*)	Additive effects of rotation and use of fertilizer: Actual increase effected by conjoining rotation and use of fertilizer
		Bushels	*Bushels*	*Bushels*	*Per cent*	*Bushels*	*Bushels*
Wheat	Rotation and use of manure	28.2	9.1	9.1	100.0	20.0	19.1
	Rotation and use of chemical fertilizer.	30.0	3.6	9.9	36.4	21.5	17.5
Corn	Rotation and use of manure	47.7	10.6	10.2	103.9	29.8	25.3
Oats	Rotation and use of manure	35.9	2.8	8.3	33.7	17.9	14.5

[1] Relative value of *R* is obtained by dividing the increase effected when rotation is added to cultivation and the use of fertilizer by the increase effected when the use of fertilizer is added to cultivation and rotation.

The results tabulated in Table 27 show that when rotation of crops is added to the use of manure, under the conditions of the Missouri tests, it is fully as effective in increasing the yields of wheat and corn as when the use of manure is conjoined with rotation of crops; or, in other words, the relative values of rotation (*R*) in effecting increases in the yields of wheat and corn are 100 per cent and 103.9 per cent. respectively. In case of oats, the relative value of *R* is

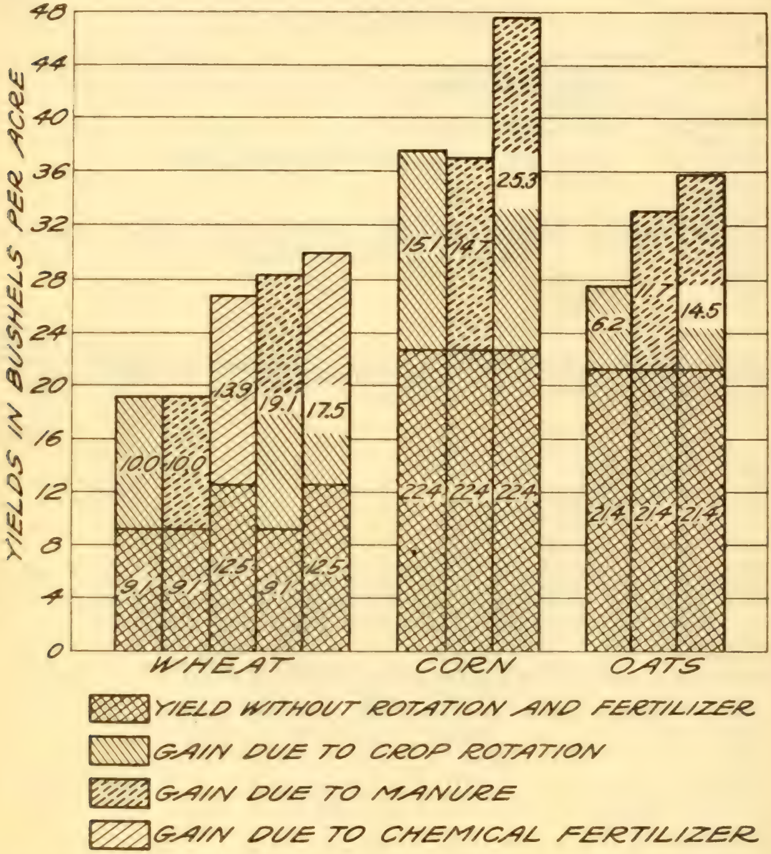

FIG. 3.—Chart visualizing the comparable yields obtained on wheat, corn, and oats at Columbia, Mo., showing the average yields that have been obtained from cultivation alone, the increase effected by combining rotation of crops or the use of fertilizers with cultivation, and the total increase effected over cultivation due to the effects of conjoining rotation and the use of fertilizer

only 33.7 per cent. In case of wheat, the increase effected by adding rotation to the use of chemical fertilizer is only 36.4 per cent as much as when the use of chemical fertilizer is added to rotation.

The figures in the last two subcolumns show that when the practices of crop rotation and the use of fertilizers are conjoined their combined effects in increasing crop yields are additive, though in each case the combined effects are somewhat less than fully additive.

Figure 3 represents in chart form the average yields of wheat, corn, and oats that have been obtained on the long-time fertility plots at

Columbia, Mo., illustrating the following results: The average yields that have been obtained from cultivation alone; the increase effected by conjoining crop rotation or the use of fertilizers with cultivation; and the total increases effected, over cultivation alone, by combining rotation and the use of fertilizers.

In each of the bars in which are shown the additive effects of combining rotation and the use of fertilizer, the diagonal hachure at the top represents the value of the use of fertilizer (*F*), and the diagonal hachure below the unhachured space represents the value of rotation (*R*). The unhachured portion represents the value of the interactive effects of rotation and the use of fertilizer when one practice is conjoined with the other; or it may show in each case how much less is the actual gain due to the conjoint effects of rotation and fertilizers than the sum of the increases effected by rotation and fertilization when practiced independently of each other, that is, the value of *r* plus the value of *f*. It can not be determined just how much of the unallocated portion of the gain should be credited to *R* and *F*, in the one case, or how much should be subtracted from the values of *r* and *f*, in the second case.

WOOSTER EXPERIMENTS WITH WHEAT, CORN, AND OATS

The fertility experiments at Wooster (*13*) were begun in 1893. Here a 5-year rotation consisting of corn, oats, wheat, clover, and timothy is under test; and the various plots are repeated five times so as to give the yields of all the crops each year. Thus in these experiments an average yield of corn, for example, in rotation for a period of successive years represents the same seasonal effects as the corresponding average yield of corn grown in continuous culture for the same years. The published results herein considered cover the 25-year period from 1894 to 1918, inclusive.

Both the rotation and continuous-culture tests at Wooster are located on a silt loam of the Wooster series. The surface soil has a yellowish-brown color and a mealy structure and is underlain by a brownish-yellow, friable stratum having a silt loam texture. The soil had been subjected to exhaustive cropping prior to 1893; and in reaction, it is acid.

In rotation, corn, oats, wheat, clover, and timothy are grown on five tracts of land, each of which is divided into 30 one-tenth-acre plots. In continuous culture, corn, oats, and wheat are grown on three tracts, each consisting of 10 one-tenth-acre plots. In all cases two fertilized plots, as Nos. 2 and 3, lie between two check plots, as Nos. 1 and 4. Four of the plots in continuous culture receive no treatment and six are fertilized, four with complete chemical fertilizers and two with farm manure.

EXPERIMENTAL DATA

In Table 28 are given the data on the fertilizers used on all the plots in continuous culture and on similarly fertilized plots in rotation. The last column of the table shows, for comparison, the average yield on each plot indicated for the 25-year period.

It is to be observed that, on the basis of the quantity of chemical fertilizers applied per acre, the most comparable yields for corn and oats are to be obtained by averaging the yields on plots 2 and 3 in continuous culture and comparing these averages, and the wheat yields on plot 2 in continuous culture, with the yields on plots 11 in rotation; and in case of manure, by averaging the yields on plots 5 and 6 in continuous culture, for wheat and corn, and comparing these averages with the yields on plot 20 in rotation. For reasons given beyond, the yields of oats on manured plot No. 5 in continuous culture are compared with those on plot 20 in rotation.

TABLE 28.—*Fertilizers used on the fertility plots at Wooster, Ohio*

[*12*, pp. 583, 588, 590, 592]

Plot	Crop	Fertilizer materials (quantities per acre)					Total per acre annually	Yield per acre (25-year average)
		Nitrate of soda	Dried blood	Acid phosphate	Muriate of potash	Manure		
		CONTINUOUS CULTURE						
		Pounds	*Pounds*	*Pounds*	*Pounds*	*Tons*	*Pounds*	*Bushels*
3	Corn	160		60	30		250	31.7
	Oats	160		55	50		265	37.3
	Wheat	120	50	45	30		245	15.7
2	Corn	160		160	100		420	40.1
	Oats	160		160	100		420	41.1
	Wheat	120	50	160	100		430	19.7
9	Corn	320		120	60		500	42.2
	Oats	320		110	100		530	45.6
	Wheat	280	50	90	60		480	21.0
8	Corn	320		160	100		580	44.9
	Oats	320		160	100		580	47.5
	Wheat	280	50	160	100		590	22.8
							Tons	
5	Corn					2.5	2.5	25.4
	Oats					2.5	2.5	29.9
	Wheat					2.5	2.5	14.3
6	Corn					5.0	5.0	35.7
	Oats					5.0	5.0	37.4
	Wheat					5.0	5.0	18.8
		ROTATION						
							Pounds	
8	Corn			80	80		160	43.8
	Oats			80	80		160	45.0
	Wheat			160	100		260	21.0
	Clover							
	Timothy							
9	Corn	160			80		240	35.5
	Oats	160			80		240	38.3
	Wheat	120	50		100		270	14.4
14	Corn	160		80	80		320	43.8
	Oats							41.0
	Wheat	120	50	160	100		430	26.1
6	Corn	160		80			240	42.8
	Oats	160		80			240	48.2
	Wheat	120	50	160			330	25.4
17	Corn	80		160	80		320	45.9
	Oats	80		160	80		320	51.1
	Wheat	60	25	160	100		345	24.3
11	Corn	160		80	80		320	46.6
	Oats	160		80	80		320	51.2
	Wheat	120	50	160	100		430	28.1
12	Corn	240		80	80		400	46.8
	Oats	240		80	80		400	50.7
	Wheat	200	50	160	100		510	28.9
							Tons	
20	Corn					4.0	4.0	43.0
	Oats							39.5
	Wheat					4.0	4.0	19.7
	Clover							
	Timothy							
18	Corn					8.0	8.0	52.6
	Oats							46.6
	Wheat					8.0	8.0	24.2

In Table 29 is shown the similarity in the fertilizer treatments given to the five plots selected, as based on the quantities of the three major nutrient elements applied per acre.

TABLE 29.—*Quantities of the major nutrient elements applied in the form of chemical fertilizers and manure to five of the selected Wooster plots*

[*12*, p. 585]

Plot	Crop	Quantity of material applied per acre	Nutrient elements (per acre)		
			Nitrogen	Phosphorus	Potassium
		Chemical fertilizer in continuous culture:	*Pounds*	*Pounds*	*Pounds*
[1] 2, 3	Corn	335 pounds annually	25	7.7	26.5
	Oats	342.5 pounds annually	25	7.5	30.7
2	Wheat	430 pounds annually	25	11.2	41.0
		Chemical fertilizer in rotation:			
11	Corn	320 pounds annually	25	5.6	32.8
	Oats	do	25	5.6	32.8
	Wheat	430 pounds annually	25	11.2	41.0
		Manure in continuous culture:			
[1] 5, 6	Corn	3.75 tons annually	33	6.9	21
	Wheat	do	33	6.9	21
5	Oats	2.5 tons annually	22	4.5	14
		Manure in rotation:			
20	Corn	4 tons	35.2	7.4	22.4
	Oats		(²)	(²)	(²)
	Wheat	4 tons	35.2	7.4	22.4

[1] Average. [2] Residual effect.

In Tables 30, 31, 32, and 33 are given in detail the yields of corn, oats, and wheat on the plots which have been selected for study, both in continuous culture and in rotation for each year from 1894 to 1913, and the average yields for the fifth 5-year period, 1914–1918. The gains per acre are also given. The gain in each case has been determined by taking the difference between the yield on the fertilized plot and the calculated yield on the same plot if it were not fertilized—the latter yield being determined by the "progressive method," assuming any variations in the soil between two successive check plots to be uniformly progressive.

TABLE 30.—*Average yields of corn, oats, and wheat, and gains per acre, on plots 2 and 3 in continuous culture for 25 years, 1894–1918, Wooster, Ohio*

Years	Yields and gains per acre (bushels)								
	Corn			Oats			Wheat		
	Plots 2 and 3 fertilized	Plots 2 and 3 unfertilized	Gain due to fertilizer	Plots 2 and 3 fertilized	Plots 2 and 3 unfertilized	Gain due to fertilizer	Plot 2 fertilized	Plot 2 unfertilized	Gain due to fertilizer
1894	22.16	18.41	3.75	31.09	25.62	5.47	19.00	13.54	5.46
1895	37.09	32.26	4.83	39.92	33.78	6.14	14.83	5.59	9.24
1896	70.57	52.05	18.52	41.80	23.13	18.67	6.08	1.18	4.90
1897	26.23	11.91	14.32	47.97	29.67	18.30	32.83	20.17	12.66
1898	52.61	30.56	22.05	41.64	26.64	15.00	26.17	11.82	14.35
5-year average	41.74	29.04	12.70	40.48	27.77	12.72	19.78	10.46	9.32
1899	40.32	20.95	19.37	45.47	25.23	20.24	18.25	2.94	15.31
1900	48.06	26.38	21.68	38.91	20.09	18.82	18.00	2.22	15.78
1901	49.82	26.46	23.36	39.45	20.04	19.41	20.75	9.80	10.95
1902	45.40	14.86	30.54	45.71	20.78	24.93	26.00	13.44	12.56
1903	32.14	8.02	24.12	21.91	4.88	17.03	26.50	12.44	14.06
5-year average	43.15	19.34	23.81	38.29	18.20	20.09	21.90	8.17	13.73
1904	24.21	4.24	19.97	56.49	31.49	25.00	8.37	4.01	4.36
1905	45.57	20.73	24.84	48.55	27.27	21.28	10.25	2.99	7.26
1906	41.69	21.59	20.10	42.22	16.61	25.61	20.17	9.64	10.53
1907	26.83	6.22	20.61	28.17	12.93	15.24	19.33	5.52	13.81
1908	27.97	12.66	15.31	40.23	17.49	22.74	28.95	8.85	20.10
5-year average	33.25	13.08	20.17	43.13	21.16	21.97	17.41	6.20	11.21
1909	30.61	10.23	20.38	37.58	17.07	20.51	27.25	10.20	17.05
1910	20.75	6.26	14.49	36.21	22.81	13.40	22.17	6.75	15.42
1911	41.00	15.80	25.20	8.59	1.40	7.19	14.67	2.08	12.59
1912	37.02	12.60	24.42	58.09	31.75	26.34	2.46	.79	1.67
1913	28.73	10.52	18.21	22.93	11.21	11.72	19.83	7.44	12.39
5-year average	31.62	11.08	20.54	32.68	16.85	15.83	17.28	5.45	11.83
5-year average, 1914–1918 [1]	29.62	11.89	17.73	41.28	20.32	20.96	22.32	8.58	13.74
25-year average	35.88	16.88	19.00	39.17	20.86	18.31	19.74	7.77	11.97

[1] Annual yields not published.

TABLE 31.—*Yields of corn, oats and wheat, and gains per acre, on plot 11 in rotation for 25 years, 1894–1918, Wooster, Ohio*

Years	Yields and gains per acre (bushels)								
	Corn			Oats			Wheat		
	Plot 11 [1] fertilized	Plot 11 if unfertilized	Gain due to fertilizer	Plot 11 fertilized	Plot 11 if unfertilized	Gain due to fertilizer	Plot 11 fertilized	Plot 11 if unfertilized	Gain due to fertilizer
1894	20.46	20.26	0.20	33.28	23.20	10.08	18.54	18.96	−0.42
1895	42.14	31.69	10.45	37.57	26.66	10.91	10.83	3.00	7.83
1896	68.57	53.86	14.71	37.34	22.09	15.25	9.04	1.28	7.76
1897	33.89	24.32	9.57	61.56	43.54	18.02	30.58	9.83	20.75
1898	41.36	22.68	18.68	48.28	37.96	10.32	33.67	15.96	17.71
5-year average	41.28	30.56	10.72	43.61	30.69	12.92	20.53	9.80	10.73
1899	37.93	24.37	13.56	58.60	36.09	22.51	22.83	5.64	17.19
1900	46.68	24.99	21.69	43.12	18.80	24.32	11.67	1.00	10.67
1901	75.89	48.88	27.01	57.03	30.78	26.25	27.25	5.94	21.31
1902	70.35	49.59	20.76	60.62	36.51	24.11	37.33	10.36	26.97
1903	18.64	4.41	14.23	43.05	21.56	21.49	38.25	20.30	17.95
5-year average	49.90	30.45	19.45	52.48	28.74	23.74	27.47	8.65	18.82
1904	36.07	14.37	21.70	66.41	46.88	19.53	26.83	8.91	17.92
1905	52.81	31.15	21.66	61.40	39.53	21.87	24.75	4.38	20 37
1906	72.75	42.02	30.73	52.90	26.92	25.98	42.70	21.01	21.69
1907	64.39	36.20	28.19	32.97	18.13	14.84	29.79	13.22	16.57
1908	44.64	26.72	17.92	53.75	44.24	9.51	41.45	21.42	20.03
5-year average	54.13	30.09	24.04	53.49	35.14	18.35	33.10	13.78	19.32
1909	38.25	17.94	20.31	53.60	33.99	19.61	34.17	20.63	13.54
1910	13.28	7.38	5.90	47.89	34.81	13.08	26.75	7.79	18.96
1911	76.36	41.55	34.81	36.79	13.23	23.56	22.00	6.45	15.55
1912	([2])	([2])	([2])	65.55	33.29	32.26	9.75	0.97	8.78
1913	37.61	15.12	22.49	24.22	9.06	15.16	39.46	22.01	17.45
5-year average	41.37	20.49	20.88	45.61	24.88	20.73	26.43	11.57	14.86
5-year average, 1914–1918 [3]	46.34	24.62	21.72	61.03	40.14	20.87	33.06	13.88	19.18
25-year average	46.60	27.24	19.36	51.24	31.92	19.32	28.12	11.54	16.58

[1] Fertilized with complete chemical fertilizer. (See Table 28.)
[2] Crop injured by white grub.
[3] Annual yields not published.

TABLE 32.—*Average yields of corn and wheat on plots 5 and 6 (manured) and of oats on plot 5 in continuous culture for 25 years, 1894–1918, Wooster, Ohio*

Years	Yields and gains per acre (bushels)								
	Corn			Oats			Wheat		
	Average of plots 5 and 6 manured	Average of plots 5 and 6 if unmanured	Average gain per acre	Plot 5 manured	Plot 5 if unmanured	Gain due to manure	Average of plots 5 and 6 manured	Average of plots 5 and 6 if unmanured	Average gain due to manure
1894	21.36	19.14	2.22	26.41	24.99	1.42	13.79	12.38	1.41
1895	43.43	29.32	14.11	33.98	33.36	0.62	9.13	4.80	4.33
1896	65.34	50.39	14.95	26.41	24.27	2.14	4.06	1.12	2.94
1897	22.64	10.03	12.61	34.06	31.46	2.60	26.71	20.42	6.29
1898	46.15	27.09	19.06	33.28	28.08	5.20	18.96	11.79	7.17
5-year average	39.78	27.19	12.59	30.83	28.43	2.40	14.53	10.10	4.43
1899	32.77	18.43	14.34	31.87	27.40	4.47	9.38	3.63	5.75
1900	43.13	23.17	19.96	29.37	21.61	7.76	11.38	2.71	8.67
1901	41.46	21.64	19.82	31.09	23.80	7.29	18.16	10.62	7.54
1902	33.88	12.88	21.00	32.19	23.12	9.07	19.83	15.74	4.09
1903	22.13	5.32	16.81	18.04	5.96	12.08	23.08	12.70	10.38
5-year average	34.67	16.29	18.38	28.51	20.38	8.13	16.37	9.08	7.29
1904	21.91	2.55	19.36	55.47	33.44	22.03	5.69	3.70	1.99
1905	44.22	15.34	28.88	40.70	29.50	11.20	8.61	2.90	5.71
1906	35.75	16.53	19.22	30.94	15.54	15.40	20.25	9.54	10.71
1907	19.03	3.04	15.99	23.98	13.49	10.49	13.54	5.97	7.57
1908	25.09	7.53	17.56	24.06	18.26	5.80	26.19	9.85	16.34
5-year average	29.20	9.00	20.20	35.03	22.05	12.98	14.86	6.40	8.46
1909	20.77	6.05	14.72	26.88	17.60	9.28	25.37	10.48	14.89
1910	18.85	3.65	15.20	30.55	23.96	6.59	22.46	6.80	15.66
1911	33.94	9.38	24.56	6.63	2.99	3.64	13.65	2.83	10.82
1912	28.62	9.11	19.51	49.30	36.94	12.36	1.87	1.00	.87
1913	20.64	5.00	15.64	17.11	10.37	6.74	18.75	9.21	9.54
5-year average	24.56	6.64	17.92	26.09	18.37	7.72	16.42	6.06	10.36
5-year average, 1914–1918 [1]	24.43	7.54	16.89	28.79	19.38	9.41	20.62	9.27	11.35
25-year average	30.53	13.33	17.20	29.85	21.72	8.13	16.56	8.18	8.38

[1] Annual yield not published.

TABLE 33.—*Yields of corn, oats, and wheat, and gains per acre, on plot 20 (manured) in rotation for 25 years, 1894–1918, Wooster, Ohio*

Years	Yields and gains per acre (bushels)								
	Corn			Oats			Wheat		
	Plot 20 manured	Plot 20 if unmanured	Gain due to manure	Plot 20 manured [1]	Plot 20 if unmanured	Gain due to manure	Plot 20 manured	Plot 20 if unmanured	Gain due to manure
1894	17.28	19.87	−2.59	23.98	24.27	−0.29	17.46	17.99	−0.53
1895	37.21	35.29	1.92	34.22	27.60	6.62	7.17	2.61	4.56
1896	55.68	50.84	4.84	26.56	24.11	2.45	4.79	1.22	3.57
1897	44.54	24.74	19.80	37.50	36.97	0.53	12.92	8.67	4.25
1898	39.86	28.31	11.55	39.68	36.09	3.59	15.04	10.65	4.39
5-year average	38.91	31.81	7.10	32.39	29.81	2.58	11.48	8.23	3.25
1899	41.32	25.52	15.80	44.06	34.69	9.37	13.50	7.75	5.75
1900	37.96	26.87	11.09	34.22	19.53	14.69	7.75	0.69	7.06
1901	49.07	38.65	10.42	38.66	31.56	7.10	14.33	6.36	7.97
1902	74.82	56.41	18.41	31.41	29.73	1.68	16.42	10.28	6.14
1903	12.21	3.82	8.39	33.91	21.48	12.43	21.33	16.20	5.13
5-year average	43.08	30.26	12.82	36.45	27.40	9.05	14.67	8.26	6.41
1904	37.25	18.96	18.29	54.06	46.61	7.45	22.21	10.00	12.21
1905	50.57	35.38	15.19	47.65	38.98	8.67	13.12	5.41	7.71
1906	53.54	36.04	17.50	37.50	28.25	9.25	37.08	22.72	14.36
1907	67.92	39.74	28.18	22.19	14.84	7.35	22.50	13.96	8.54
1908	42.25	27.67	14.58	48.59	41.82	6.77	27.46	17.68	9.78
5-year average	50.31	31.56	18.75	42.00	34.10	7.90	24.47	13.95	10.52
1909	43.11	23.44	19.67	45.39	34.87	10.52	33.21	22.41	10.80
1910	20.35	6.14	14.21	46.09	38.59	7.50	23.54	7.76	15.78
1911	61.89	35.15	26.74	32.73	16.51	16.22	20.33	7.42	12.91
1912	([2])	([2])	([2])	40.07	31.47	8.60	6.33	1.17	5.16
1913	31.50	13.52	17.98	17.42	13.30	4.12	26.54	16.87	9.67
5-year average	39.21	19.56	19.65	36.34	26.95	9.39	21.99	11.12	10.87
5-year average, 1914–1918 [3]	42.52	24.89	17.63	50.42	40.66	9.76	25.83	14.84	10.99
25-year average	42.81	27.62	15.19	39.52	31.78	7.74	19.69	11.28	8.41

[1] Residual effect of manure applied to corn. No direct manure application made on oats in rotation.
[2] Injury by white grub.
[3] Annual yields not published.

The oat crop on plot 20 in rotation does not receive any direct application of manure, but it receives the residual effect of the 4 tons of manure applied to the preceding corn crop. In continuous culture, the nearest approach to yields comparable with the oat yields on plot 20 in rotation are those obtained on plot 5, which receives an annual application of 2.5 tons of manure per acre. This explains why the oat yields in rotation are compared with those on plot 5 in continuous culture, instead of with the average of the yields obtained on plots 5 and 6, as in case of the wheat and corn.

RESULTS WHEN ROTATION AND FERTILIZATION ARE PRACTICED INDEPENDENTLY

From the 25-year averages given in Tables 30, 31, 32, and 33, Table 34 is constructed, summarizing the average yields per acre and the increases over check plots in continuous culture, and showing the relative values of crop rotation in increasing crop yields when rotation and the use of fertilizers are practiced independently of each other.

TABLE 34.—*Effects of crop rotation and of the use of fertilizers on the yields of wheat, corn, and oats. Wooster, 25-year results*

(Rotation and fertilization practiced separately)

Plot	Crop	Cultural conditions	Average yield per acre	Increase over check plot in continuous culture	Relative value of crop rotation, as compared with fertilizers, in effecting larger yields
			Bushels	*Bushels*	*Per cent*
11	Wheat	Crop rotation without the use of chemical fertilizer (*r*)	11.54	3.77	31.5
2		Use of chemical fertilizer without crop rotation (*f*)	19.74	11.97	
20		Crop rotation without the use of manure (*r*)	11.28	3.10	37.0
[1] 5, 6		Use of manure without crop rotation (*f*)	16.56	8.38	
11	Corn	Crop rotation without the use of chemical fertilizer (*r*)	27.24	10.36	54.5
[1] 2, 3		Use of chemical fertilizer without rotation (*f*)	35.88	19.00	
20		Crop rotation without the use of manure (*r*)	27.62	14.29	83.1
[1] 5, 6		Use of manure without rotation (*f*)	30.53	17.20	
11	Oats	Crop rotation without the use of chemical fertilizer (*r*)	31.92	11.06	60.4
[1] 2, 3		Use of chemical fertilizer without rotation (*f*)	39.17	18.31	
20		Crop rotation without the use of manure (*r*)	31.78	10.06	123.7
5		Use of manure without rotation (*f*)	29.85	8.13	

[1] Average.

The comparative separate effects of crop rotation and the use of fertilizers in effecting larger yields of wheat, corn, and oats, under the conditions of the Wooster experiments, are reflected in the relative values of rotation. Here it is shown that, in each case, the rotation effects in the manure series are relatively higher than in the chemical-fertilizer series, the average relative values for rotation being 81.3 per cent and 48.8 per cent, respectively, for the two series.

RESULTS WHEN CROP ROTATION AND THE USE OF FERTILIZERS ARE CONJOINED

In Table 35 are summarized the results of the Wooster experiments when rotation of crops and the use of fertilizers are combined, showing the relative values for rotation (*R*) and the additive effects of conjoining rotation and the use of fertilizers.

TABLE 35.—*Relative values of rotation* (*R*) *and additive effects of conjoining rotation and the use of fertilizers, Wooster, Ohio*

Crop	Cultural conditions	Average yield per acre	Values for *R* and *F*		Relative value of *R*	Additive effects of rotation and use of fertilizers	
			R	*F*		Sum of increases effected by rotation and use of fertilizer when practiced separately (*r*+*f*)	Actual increase effected by conjoining rotation and use of fertilizers
		Bushels	*Bushels*	*Bushels*	*Per cent*	*Bushels*	*Bushels*
Wheat	Rotation and use of chemical fertilizer	28.12	8.38	16.58	50.5	15.74	20.35
	Rotation and use of manure	19.69	3.13	8.41	37.2	11.48	11.51
Corn	Rotation and use of chemical fertilizer	46.60	10.72	19.36	55.4	29.36	29.72
	Rotation and use of manure	42.81	12.28	15.19	80.8	31.49	29.48
Oats	Rotation and use of chemical fertilizer	51.24	12.07	19.32	62.5	29.37	30.38
	Rotation and use of manure [1]	39.52	9.67	7.74	124.9	18.19	17.80

[1] Residual effects, manure is applied to corn and wheat in the rotation. (See Table 28.)

These experiments on wheat, corn, and oats at Wooster show that rotation of crops, when joined to the use of chemical fertilizer, is 56.1 per cent as effective in increasing crop yields as the use of chemical fertilizer when joined to rotation of crops, as is indicated by the relative values of *R*. When compared with the use of manure, rotation (*R*) has a higher efficiency than when compared with the use of chemical fertilizer, as is indicated by an average relative value of 81.0 per cent for *R*.

The figures in the last two subcolumns show that the conjoint effects of rotation and the use of fertilizers, in effecting increases

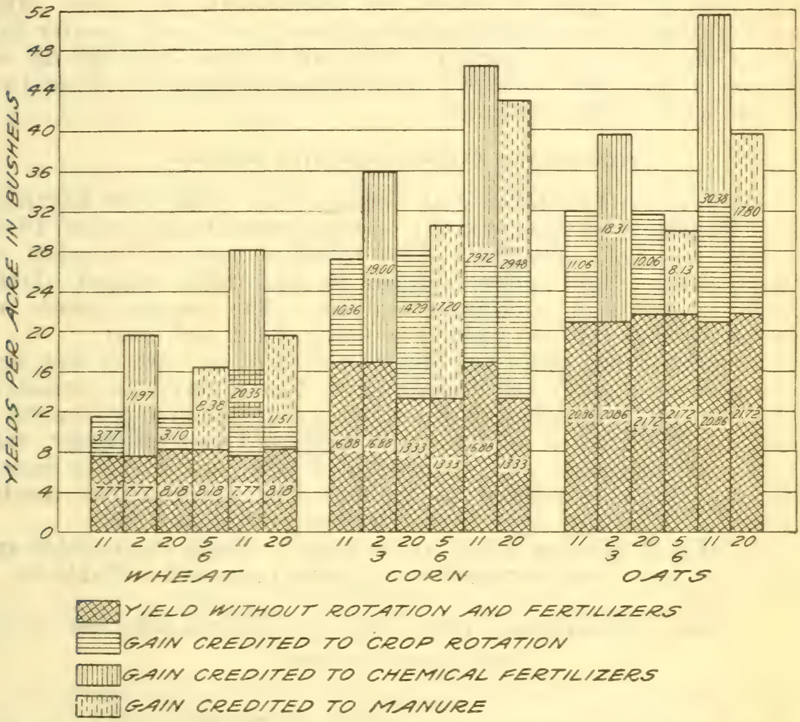

FIG. 4.—Chart summarizing the rotation and fertilizer results obtained on wheat, corn, and oats at Wooster, Ohio, showing the average yields that have been obtained from cultivation alone, the increases effected when to cultivation is added rotation or the use of fertilizer, and the increases obtained (over cultivation) due to the conjoint effects of rotation and the use of fertilizers. The numbers below the bars are the plot numbers

above the check-plot yields in continuous culture, are practically fully additive, except in case of the combined effects of rotation and the use of chemical fertilizer on wheat, where the effects are more than fully additive.

In Figure 4 are summarized in diagrammatic form the results obtained at Wooster, as follows: The average yields of wheat, corn, and oats that have been obtained from cultivation alone, that is, without rotation and fertilizer; the increases obtained when with cultivation is combined the practice of crop rotation or the use of fertilizer; and the increase over cultivation due to the combined effects of rotation and the use of fertilizer.

In the last two bars of each series the horizontal and vertical hachure may be interpreted to represent either the values for *R* and *F* (the increases effected by rotation when added to the use of fertilizers and the increases effected by the use of fertilizers when added to rotation) or the values of *r* and *f* (the increases effected by rotation and the use of fertilizers when practiced independently of each other).

It is to be noted that in the bar showing the yield of wheat on plot 11 (rotation and fertilizer) the hachure showing the values for rotation (*R*) and fertilizers (*F*) overlap to the extent of 4.61 bushels, as indicated by the horizontal-vertical crosshatching. This value of 4.61 bushels measures the interactive effects of rotation and the use of chemical fertilizer when the two practices are conjoined. The horizontal-vertical crosshatching also shows how much greater the increase effected by the conjoint action of rotation and the use of fertilizer is than the sum of the increases effected by these two practices when acting separately.

GERMANTOWN EXPERIMENTS WITH TOBACCO

The experiments on tobacco at Germantown, Ohio, were begun in 1903. Published results cover the 16-year period from 1903 to 1918, inclusive (*12, pp. 629–634*). The rotation involved consists of tobacco, wheat, and clover, grown in the order named. Only tobacco is grown in continuous culture. The rotation plots are repeated, so that tobacco yields are obtained for each year.

The Germantown plots are one-twentieth of an acre in size and are located on a heavy soil designated as Miami clay loam, which is the product of the weathering of a thick bed of glacial drift composed largely of the detritus of limestone rocks. Thus, originally, this soil was well supplied with carbonate of lime, and for this reason tobacco has not responded to liming. The experimental results selected for this study have been obtained on unlimed soil.

The yields of tobacco which are nearest to being comparable are those which have been obtained on the plots indicated in Table 36.

TABLE 36.—*Soil treatment and yields on Germantown, Ohio, plots*

[16-year averages, 1903–1918]

System of cropping	Plot	Crop	Fertilizer materials used (per acre to tobacco)				Average yields per acre
			Nitrate of soda	Acid phosphate	Muriate of potash	Manure	
			Pounds	*Pounds*	*Pounds*	*Tons*	*Pounds*
Continuous culture	9	Tobacco	320	320	120		1,064
	11, 14, 17	do				[1] 8	875
Rotation	12	Tobacco	240	480	120		1,141
		Wheat					
		Clover					
	32	Tobacco				10	993
		Wheat					
		Clover					

[1] Same treatment on each plot.

The data of the tobacco yields on the selected Germantown plots are summarized in Tables 37 and 38.

TABLE 37.—*The effects of crop rotation and the use of fertilizers on the yields of tobacco, Germantown, Ohio*

[Rotation and use of fertilizers practiced separately]

Plot No.	Cultural conditions	Average yield per acre	Increase over check plot in continuous culture	Relative value of crop rotations, as compared with fertilizers, in effecting increases over cultivation alone
		Pounds	*Pounds*	*Per cent*
12	Crop rotation without the use of chemical fertilizer (*r*)	524	213	28.3
9	Use of chemical fertilizer without rotation (*f*)	1,064	753	
9	Without rotation and without the use of chemical fertilizer	311		
32	Crop rotation without the use of manure (*r*)	512	177	32.8
11, 14, 17	Use of manure without rotation (*f*)	875	540	
1, 4, 7, 10	Without rotation and without the use of manure	335		

NOTE.—Because of the arrangement of the manured plots in continuous culture it seemed advisable to average the yields on plots 1, 4, 7, and 10 to obtain a check-plot yield in the manure series.

TABLE 38.—*Relative values of rotation (R) and additive effects of conjoining rotation and the use of fertilizers*

[Tobacco, Germantown, Ohio]

Cultural conditions	Average yield per acre	Values of *R* and *F*		Relative value of *R*	Additive effects of rotation and use of fertilizer	
		R	*F*		Sum of increases effected by rotation and use of fertilizer when practiced separately (*r*+*f*)	Actual increase effected by conjoining rotation and use of fertilizers
	Pounds	*Pounds*	*Pounds*	*Per cent*	*Pounds*	*Pounds*
Rotation and use of chemical fertilizer	1,141	77	617	12.5	966	830
Rotation and use of manure	993	118	481	24.5	717	658

These results show that under the conditions of the Germantown test, the 3-year rotation of tobacco, wheat, and clover is only 28.3 per cent as effective as the use of 840 pounds of a complete fertilizer per acre and only 32.8 per cent as effective as the use of 10 tons of manure when rotation and use of fertilizers are practiced independently of each other, and only 12.5 per cent and 24.5 per cent as effective as the use of chemical fertilizer and manure, respectively, when the one practice is combined with the other.

The combined effects of rotation and the use of chemical fertilizer or manure are somewhat less than fully additive; that is, in effecting increases in the yields of tobacco over the check plots in continuous culture.

URBANA EXPERIMENTS WITH CORN

The Morrow plots at Urbana, Ill., furnish results on corn which may be given consideration in this study of the value of crop rotation. The Morrow field "consists of three plots divided into halves. On one corn is grown continuously, on the second corn and oats are grown in rotation, and on the third, corn, oats, and clover (in rotation). The north half of each plot is untreated, whereas the south half receives standard applications of manure with cover crops (in the one-crop and two-crop systems). Rock phosphate is applied to the southwest one-fourth of each plot at the rate of 600 pounds, and steamed bone meal to the southeast one-fourth at the rate of 200 pounds per acre per year. In 1904 ground limestone was applied at the rate of 1,700 pounds per acre to the south half of each plot." (*6, pp. 486 and 487.*)

These experiments were begun in 1888 on land formerly highly productive. Comparable yields of corn—that is, yields on fertilized and unfertilized land in continuous culture and in rotation, begin with the year 1904 corn being the only crop that is grown in continuous culture.

The Morrow plots are located on a prairie soil described as a brown silt loam which has probably developed from the weathering of glacial material deposited during the early Wisconsin glaciation. In reaction the soil had become somewhat acid.

In Table 39 are given the comparable yields of corn obtained in continuous culture and in rotation at Urbana.

TABLE 39.—*Yields of corn in continuous culture and in rotation, Urbana, Ill., 1904–1916*

Years	Continuous culture [1]		Rotation (corn, oats, and clover)	
	Fertilized (MLP)[2]	Unfertilized	Fertilized (MLP)[2]	Unfertilized
	Bushels	*Bushels*	*Bushels*	*Bushels*
1904	17.1	21.5	72.7	55.3
1907	48.7	29.0	93.6	80.5
1910	54.6	35.9	83.3	58.6
1913	32.0	19.4	47.8	33.8
1916	10.8	11.2	40.6	27.8
Average, 5 crops	32.6	23.4	67.6	51.2

[1] A cover crop is grown on the continuous-culture plot, but not on the rotation plot. This balances, at least in part, the heavier applications of manure made on the rotation plots.
[2] M (manure), standard application, the quantity that can be produced from the produce grown. P (phosphorus), bone meal and rock phosphate. L (pulverized limestone).

The results of a study of the average yields given in Table 39 are summarized in Tables 40 and 41.

TABLE 40.—*Effects of rotation and of the use of fertilizers on the yields of corn, Urbana, Ill.*

[Rotation and fertilization practiced separately]

Cultural conditions	Average yield per acre	Increase over check plot in continuous culture	Relative value of rotation, as compared with fertilizers, in effecting larger yields
	Bushels	*Bushels*	*Per cent*
Crop rotation without the use of fertilizers (*r*)	51.2	27.8	302.2
Use of fertilizers without rotation (*f*)	32.6	9.2	
No rotation and no fertilizer	23.4		

TABLE 41.—*Relative value of rotation (R) and additive effects of conjoining rotation and the use of fertilizers, Urbana, Ill.*

Cultural conditions	Average yield per acre	Values of *R* and *F*		Relative value of *R*	Additive effects of rotation and use of fertilizers	
		R	*F*		Sum of increases effected by rotation and use of fertilizer when practiced separately (*r*+*f*)	Actual increase effected by conjoining rotation and use of fertilizers
	Bushels	*Bushels*	*Bushels*	*Per cent*	*Bushels*	*Bushels*
Rotation and use of fertilizers	67.6	35.0	16.4	213.4	37.0	44.2
Rotation without use of fertilizers	51.2					
Use of fertilizers without rotation	32.6					

These results indicate that, under the conditions of the Urbana experiments, crop rotation is three times as effective as the use of fertilizers in increasing the yield of corn, over cultivation alone, when rotation and the use of fertilizers are practiced independently of each other; and when one practice is conjoined with the other, rotation (*R*) is over twice as effective as the use of fertilizers (*F*). And further, when rotation and the use of fertilizers are conjoined, their combined effects are more than fully additive, as determined by the increase in yield over the check plot in continuous culture.

The results obtained on the Urbana field are visualized in Figure 5. It is to be observed that the hachure showing the values for *R* and *F* overlap to the extent of 7.2 bushels, as indicated by the crosshatching. This measures the interactive effects of rotation and the use of fertilizer when these practices are combined, and it shows how much greater the increase effected by conjoining rotation and fertilization is than the sum of the gains resulting when rotation and the use of fertilizers are practiced separately.

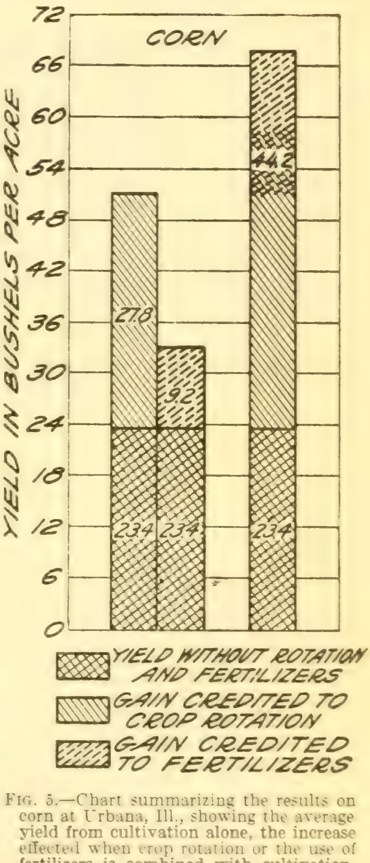

FIG. 5.—Chart summarizing the results on corn at Urbana, Ill., showing the average yield from cultivation alone, the increase effected when crop rotation or the use of fertilizers is combined with cultivation, and the increase effected by the conjoint effects of rotation and the use of fertilizers

FLORENCE EXPERIMENTS WITH COTTON

The South Carolina results herein considered are those obtained with wilt-resistant cotton (Dixie variety) on the rotation and continuous-culture plots of the Pee Dee Experiment Station located at

Florence, S. C. (*1*). Though these experiments have not been in progress very long, having been started in 1914, they are the best obtainable on cotton at this time.

The rotation concerned is a 3-year system, described as follows: First year, corn and cowpeas; second year, oats followed by cowpeas; third year, cotton.

All the rotation plots are repeated three times, as series A, B, and C, so that cotton yields are obtained for each year. Only cotton is grown in continuous culture (series D). The plots in both the rotation and continuous-culture series are numbered in the same order and the corresponding individual plots in each series are fertilized alike.

The soil on which these cotton experiments are located is a very fine sandy loam of the Orangeburg series. Under cultivation, the surface stratum of this soil is of a grayish color, becoming pale yellow at a depth of about 5 or 6 inches. At depths of from 10 to 15 inches, the soil consists of a red, friable fine sandy clay. In reaction the soil is somewhat acid.

In the Pee Dee station experiments no manure is used, hence comparable yields are confined to the results obtained from the use of chemical fertilizers. Three of the plots, 24, 27, and 30, are fertilized annually with a complete fertilizer equivalent to a 1,000-pound application of a 4–8–4 [2] commercial mixture. Inasmuch as these three plots are given favorable fertilizer treatments, as indicated by the average yields of cotton, these plots have been selected for comparable yields. In Table 42 are given the fertilizer treatments and the average yields obtained on these three plots both in continuous culture and in rotation, compared with the treatments and yields of some of the other plots.

TABLE 42.—*Fertilizer treatments and yields of cotton on some of the experimental plots at Florence, S. C.*

[6-year averages]

Plot	Fertilizer materials (pounds per acre)					Yields per acre of seed cotton (pounds)	
	Dried blood	Cottonseed meal	Acid phosphate	Muriate of potash	Kainit	Continuous culture	Rotation
7	250					1,342	1,417
2			500			1,335	1,699
5				83.3		1,140	1,521
6					333.3	1,240	1,485
12	250		500			1,522	1,776
16	250			83.3		1,692	1,650
15	250				333.3	1,725	1,672
8			500	83.3		1,255	1,675
24	250		500	83.3		1,877	1,925
27	83.3	380	450		333.3	1,862	1,846
30	83.3	380	450	83.3		1,710	1,870
34	250		250	83.3		1,680	1,880
35	250		1,000	83.3		1,695	1,955
36	125		500	83.3		1,597	1,846
37	500		500	83.3		1,785	1,916

[2] In South Carolina and some of the othern Southern States this analysis is expressed as 8–4–4, the 8 per cent referring to P_2O_5.

On each of the three selected plots, 24, 27, and 30, are applied annually the same quantities of the major nutrient elements. On the rotation plots like applications are made for corn and oats, so that for each 3-year period the same quantities of fertilizing ingredients are applied per acre in rotation as in continuous culture.

In Table 43 are given the average annual yields of seed cotton per acre and gains from fertilizers on the three selected plots in continuous culture and in rotation for the period reported. The results recorded in Table 43 are from unlimed plots.

TABLE 43.—*Annual yields of seed cotton and gains per acre on experimental plots at Florence, S. C.*

Years	Continuous culture			Rotation		
	Fertilized average 24, 27, 30	Check plots average 21 and 31	Gain from fertilizer	Fertilized average 24, 27, 30	Check plots average 21 and 31	Gain from fertilizer
	Pounds	*Pounds*	*Pounds*	*Pounds*	*Pounds*	*Pounds*
1914	2,120	1,958	162	1,960	1,665	295
1915	1,995	1,523	472	2,195	1,575	620
1916	1,060	878	182	1,023	1,407	−384
1917	1,800	1,080	720	1,605	1,388	217
1918	2,320	1,230	1,090	2,375	1,838	537
1919	1,605	1,260	345	2,125	1,853	272
6-year average	1,816	1,321	495	1,880	1,621	259

It is to be noted that the average gain from fertilizers is greater without rotation than with rotation; nevertheless, the average yield on the fertilized plots in rotation is greater than that on the corresponding plots in continuous culture.

In Tables 44 and 45 are given the evaluations of rotation and the additive effects of rotation and the use of fertilizer.

TABLE 44.—*The effects of rotation and of the use of fertilizer on the yields of seed cotton*

[Rotation and fertilization practiced separately]

Cultural conditions	Average yield per acre	Increase over check plot in continuous culture	Relative value of rotation, as compared with fertilizers, in effecting larger yields
	Pounds	*Pounds*	*Per cent*
Crop rotation without the use of fertilizer (*r*)	1,621	300	60.6
Use of fertilizer without rotation (*f*)	1,816	495	
No rotation and no fertilizer	1,321		

TABLE 45.—*Relative value of rotation (R) and additive effects of conjoining rotation and the use of fertilizers*

Cultural conditions	Average yield of seed cotton per acre	Values of R and F		Relative value of R	Additive effects of rotation and use of fertilizers	
		R	F		Sum of increases effected by rotation and use of fertilizer when practiced separately (r+f)	Actual increase effected by conjoining rotation and use of fertilizers
	Pounds	*Pounds*	*Pounds*	*Per cent*	*Pounds*	*Pounds*
Rotation and use of fertilizers	1,880	64	259	24.7	795	559
Rotation without fertilizer	1,621					
Use of fertilizer without rotation	1,816					

These results with cotton obtained under the conditions of the South Carolina experiments show that when crop rotation and the use of fertilizers are practiced independently of each other, rotation is 60.6 per cent as efficient as the use of fertilizers in effecting increases in the yield, as measured from the check plot in continuous culture. On the other hand, when rotation is conjoined with the use of fertilizers it is only about 25 per cent as efficient in effecting increases in the yield as the use of fertilizer when conjoined with rotation of crops. In other words, the value for *R* is only about one-fourth as great as the value for *F*. These results also show that the conjoint effects of rotation and the use of fertilizers on the yield of cotton are additive, though less than fully additive.

The chart in Figure 6 is a graphic summary of these South Carolina results on cotton, showing the average yield obtained from cultivation alone, the gain resulting when to cultivation is added rotation or the use of chemical fertilizer, and the average gain obtained when to cultivation are added rotation and the use of fertilizer. In the third bar, the diagonal hachures represent the values for *R* and *F*. The unhachured space, representing an unallocated gain of 236 pounds, measures the interactive effects of rotation and the use of fertilizer when one practice is conjoined with the other; and it also shows how much less the increase effected by the conjoint action of rotation and fertilizers is than the sum of the gains effected by rotation and the use of fertilizers when practiced independently of each other.

ROTATION AND FERTILIZER EFFICIENCIES AS AFFECTED BY SOIL REACTION

With the exception of the Illinois results on corn, where the soil treatment consists of applications of ground limestone, manure, and phosphates, and the Rothamsted experiments, the experimental data presented in the foregoing tables have been obtained on soils that are somewhat acid in character. It is a fact universally recognized that, when the acidity of soils having from medium to strong degrees of acidity is reduced or corrected, the average yields of the crops in a rotation are usually increased, regardless of the fact that some of the crops in the rotation, other than clover or alfalfa, may show but little or no response to a direct application of lime.

In this study of the comparative effects of rotation and the use of fertilizers, all of the long-time liming tests can not be considered, but only those that meet with the conditions which make possible the evaluations of the effects of crop rotation and the use of fertilizers on crop yields. The liming tests that are thus in harmony with these conditions are those on wheat, corn, and oats at Wooster, Ohio, and those of a shorter duration on cotton at Florence, S. C.

The published results of the Wooster experiments are for the rotation plots only, including a 13-year test on wheat (1906–1918), a 19-year test on corn (1900–1918), and a 15-year test on oats (1901 and 1905–1918) (*12, pp. 598–601*). The 6-year results (1914–1919) reported on cotton by the South Carolina Experiment Station are for both the rotation and continuous-culture plots (*1*).

Since lime is applied to the west ends of the Wooster rotation plots, the plots selected for comparable yields in these liming tests are the same as those heretofore chosen (see Table 29), the average yields for each crop being determined for its liming period, on both the limed and unlimed plots. In case of the South Carolina cotton experiments, those plots were selected which receive the same fertilizer treatments under both limed and unlimed conditions, as shown in Table 46.

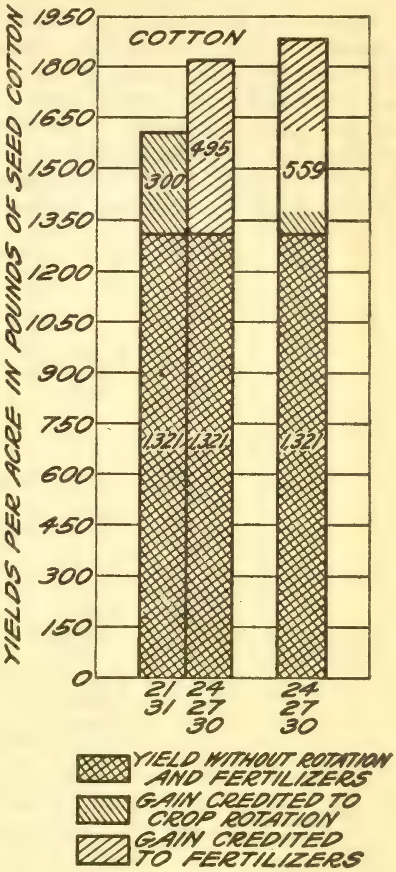

FIG. 6.—A graphic summary of the comparable yields of cotton obtained at Florence, S. C., showing the average yield obtained from cultivation alone, the gain resulting when to cultivation is added crop rotation or the use of chemical fertilizer, and the total increase effected when to cultivation are added both rotation and the use of fertilizer. The numbers at the bottom of the bars are the plot numbers

TABLE 46.—*Limed and fertilized plots at Florence, S. C.*[1]

Lime treatment (per acre)	Plot	Fertilizer treatment
No lime	[2] 11, 21, 31	No fertilizer.
	24	250 pounds dried blood, 500 pounds acid phosphate, 83.3 pounds muriate of potash.
1,000 pounds burnt lime	17	No fertilizer. Results averaged.
2,000 pounds ground limestone	18	
1,000 pounds burnt lime	22	Same fertilizer treatment as on plot 24. Results averaged.
2,000 pounds ground limestone	23	

[1] Plots are numbered the same in the continuous-culture series for cotton as in the rotation series.
[2] Average.

In Table 47 is given a summary of the average yields of wheat, corn, and oats grown in rotation on limed and unlimed soil at Wooster, Ohio, and of cotton at Florence, S. C., for the periods indicated. For comparison, the yields of other crops, not included in the study of rotation values, are added; namely, those of clover and timothy on the same Wooster plots, of oats, corn, and peavine hay (cowpeas) on the plots at Florence, and also the yields of corn, oats, wheat, and hay on the long-continued Pennsylvania plots (Hagerstown silt loam). In the last right-hand column are given the absolute measures, in bushels or pounds, of the increase in fertilizer efficiency due to the alteration of the soil reaction as effected by liming.

TABLE 47.—*Effect of liming on the efficiency of fertilizers*

Crop	Period of test	Fertilizer treatment (crops grown in rotation)	Units of measure	Average yield per acre on acid soil [2]	Average yield per acre on same soil limed [3]	Increase due to liming	Increase in fertilizer efficiency due to alteration of soil reaction [4]
Wheat (Wooster)	1906–1918 (13 years).	Complete chemical fertilizer.[1]	Bushels	31.7	32.2	0.5	0.0
		Manure	do	25.1	26.8	1.7	.0
Corn (Wooster)	1900–1918 (19 years).	Complete chemical fertilizer.	do	48.9	54.5	5.6	1.4
		Manure	do	44.2	48.9	4.7	.5
Oats (Wooster)	1901 and 1905–1918 (15 years).	Complete chemical fertilizer.	do	52.8	53.2	0.4	.0
		Manure	do	41.9	44.0	2.1	.0
Cotton (South Carolina).	1914–1919 (6 years).	Complete chemical fertilizer.	Pounds	1,925	1,929	4.0	68
Clover (Wooster)	1903–1918 (16 years).	do	do	2,496	3,320	824	191
		Manure	do	2,246	3,011	765	115
Timothy (Wooster).	1906–1918 (13 years).	Complete chemical fertilizer.	do	3,117	4,095	978	109
		Manure	do	3,205	4,433	1,228	256
Oats (South Carolina).	1914–1919	Complete chemical fertilizer.	Bushels	60.4	60.0	−0.4	.6
Corn (South Carolina).	do	do	do	54.8	56.8	2.0	.7
Peavine hay (South Carolina)	do	Complete chemical fertilizer.	Pounds	2,473	2,434	−39.0	.0
Corn (Pennsylvania).	1882–1921	Manure (6 tons per acre).[5]	Bushels	56.3	62.5	6.2	5.2
Oats (Pennsylvania).	do	Manure (residual effects.	do	42.1	43.7	1.6	2.2
Wheat (Pennsylvania).	do	Manure (6 tons per acre).	do	23.8	23.8	.0	.0
Hay (Pennsylvania).	do	Manure (residual effects).	Pounds	3,804	4,223	419	275

[1] See Tables 29 and 46 for plots and fertilizer treatments at Wooster and Florence.
[2] Yields for liming period at Wooster calculated from Tables 31 and 33; for cotton, Bull. 209, S. C. Exper. Sta., p. 4.
[3] For Ohio yields, Bull. 336 Ohio Exper. Sta., pp. 599–601.
[4] Calculated from results published in bulletins to which reference has been made.
[5] Bull. 175, Pa. Exper. Sta., p. 9. Plots included are: Average 1, 8, 14, 24, and 36, check plots; 16, manure but no lime; 23, burnt lime but no manure; 22, manure and burnt lime.

Two important facts are brought out in the results given in Table 47: (1) Though the yield of a nonleguminous crop fertilized and grown in rotation may average larger on an acid soil whose reaction has been altered by liming than on the same soil unlimed, the greater yield may not at all be due to any increase in the efficiency of the fertilizer as may have been effected by the alteration or change of the soil reaction; (2) under similar conditions, as described under (1), only a portion of the increase in yield may be due to increased efficiency of the fertilizer used.

These differences in the relation of crop yields to fertilizer results are determined by the interaction of three factors: Fertilizer, crop, and crop rotation.

Whether or not a fertilizer will produce higher results on an acid soil when its reaction has been altered by liming depends in a large measure on the chemical character of the fertilizer. Experimental data show that (1) for most farm crops, the highest efficiency of an acidic fertilizer is effected on a nonacid soil or on an acid soil that has been limed; (2) under the same soil conditions, a basic fertilizer usually gives the best, or at least as good results without liming. These two points are strikingly illustrated by the results obtained on rotation plots 24 and 29 in the long-time liming tests conducted at Wooster, Ohio, as shown in Table 48.

TABLE 48.—*Relation of fertilizer efficiency to change in soil reaction as affected by liming, Wooster, Ohio*

Plot	Crop	Fertilizer composition	Unit of measure	Average yield per acre on acid soil, unlimed	Average yield per acre on acid soil, limed	Increase or decrease in fertilizer efficiency [1]
		Acidic compound				
24	Corn	Ammonium sulphate, acid phosphate, and muriate of potash.	Bushels	45.79	55.35	+3.52
	Oats	do	do	51.46	54.64	−2.98
	Wheat	do	do	24.41	30.63	+1.33
	Clover	do	Pounds	1,986	3,374	+801.00
	Timothy	do	do	2,740	4,365	+712.00
		Basic compound				
29	Corn	Nitrate of soda, basic slag, and muriate of potash.	Bushels	45.58	51.16	−0.13
	Oats	do	do	50.67	50.39	−4.66
	Wheat	do	do	29.35	28.76	−4.00
	Clover	do	Pounds	2,823	3,221	−136.00
	Timothy	do	do	3,384	4,107	−90.00

[1] Calculated from data given in the bulletins to which reference has been made.

Attention is called to the behavior of the oat crop, which, under the conditions of the Wooster experiments, seems to favor acid conditions, and thus has not been benefited by liming. Furthermore, the oat plant commonly shows a preference for ammonium salts, probably because of its ability to utilize nitrogen in ammonia form. Corn also exhibits the same assimilation ability (*7, p. 179*).

When, in a long-continued cropping system, an alteration or change of the soil reaction by liming does not effect a greater fertilizer efficiency, even though the yield of a crop is larger because of the liming, particularly when the crop shows but little or no response to a direct application of lime, it becomes plainly evident that crop rotation is the factor which assumes the greatest prominence in the maintenance of soil productivity under liming conditions. It is possible to evaluate crop rotation under these conditions only when experimental data present comparable yields both in rotation and in continuous culture. The only experimental data so far published that are in harmony with these conditions are those on the first four crops mentioned in Table 47, which are described in the foregoing paragraphs.

In Table 49 are given the analyses of the average yields of these four crops for the periods indicated in Table 47, when rotation and the use of fertilizers are practiced independently of each other.

TABLE 49.—*The comparative effects of crop rotation and of the use of fertilizers on the yields of crops on limed and unlimed soils*

[Rotation and the use of fertilizers practiced separately]

Crop	Cultural conditions	Average yield per acre	Increase over check plot in continuous culture	Relative value of rotation, as compared with fertilizers, in effecting larger yields
		Bushels	*Bushels*	*Per cent*
Wheat (Wooster)	Limed:[1]			
	Rotation without use of chemical fertilizer	16.0		
	Rotation without use of manure	16.2		
	Unlimed:			
	Rotation without use of chemical fertilizer	14.1	6.9	51.9
	Use of chemical fertilizer without rotation	20.5	13.3	
	No rotation and no fertilizer	7.2		
	Rotation without the use of manure	14.2	6.3	57.3
	Use of manure without rotation	18.9	11.0	
	No rotation and no manure	7.9		
Corn (Wooster)	Limed:			
	Rotation without use of chemical fertilizer	31.1		
	Rotation without use of manure	31.2		
	Unlimed:			
	Rotation without use of chemical fertilizer	26.9	13.4	65.0
	Use of chemical fertilizer without manure	34.1	20.6	
	No rotation and no fertilizer	13.5		
	Rotation without use of manure	27.0	17.6	94.6
	Use of manure without rotation	28.0	18.6	
	No rotation and no manure	9.4		
Oats (Wooster)	Limed:			
	Rotation without use of chemical fertilizer	35.1		
	Rotation without use of manure	35.6		
	Unlimed:			
	Rotation without use of chemical fertilizer	32.3	13.6	70.8
	Use of chemical fertilizer without rotation	37.9	19.2	
	No rotation and no fertilizer	18.7		
	Rotation without use of manure	32.9	13.6	149.5
	Use of manure without rotation	28.4	9.1	
	No rotation and no manure	19.3		
		Pounds	*Pounds*	
Cotton (South Carolina.)	Limed:			
	Rotation without use of chemical fertilizer	1,584	369	57.2
	Use of chemical fertilizer without rotation	1,860	645	
	No rotation and no fertilizer	1,215		
	Unlimed:			
	Rotation	1,648	359	61.1
	Use of chemical fertilizer without rotation	1,877	588	
	No rotation and no fertilizer	1,289		

[1] No lime is applied to the plots in continuous culture at Wooster.

The data in Table 50 show that the yields of wheat, corn, and oats are higher on the limed than on the unlimed soils. Cotton has not responded to liming. Altering the soil reaction has caused a decline in the relative value of rotation in the case of cotton. The absence of liming tests in continuous culture makes it impossible to determine the relative values of rotation in case of wheat, corn, and oats, under conditions when rotation and the use of fertilizers are practiced apart from each other.

In Table 50 are summarized the data on the yields when rotation and the use of fertilizers are conjoined.

TABLE 50.—*Comparison of relative values of rotation (R) and of the additive effects of conjoining rotation and the use of fertilizers on limed and unlimed soils*

[Wooster, Ohio, and Florence, S. C.]

Crop	Cultural conditions	Average yield per acre	Values for R and F: R	Values for R and F: F	Relative value of R	Additive effects of rotation and use of fertilizers: Sum of increase effected by rotation and use of fertilizer when practiced separately (r+f)	Additive effects of rotation and use of fertilizers: Actual increase effected by conjoining rotation and use of fertilizers
		Bushels	*Bushels*	*Bushels*	*Per cent*	*Bushels*	*Bushels*
Wheat (Wooster)	Limed:						
	Rotation and use of chemical fertilizer.	32.2	11.7	16.2	72.2	22.1	25.0
	Rotation without chemical fertilizer.	16.0					
	Use of chemical fertilizer without rotation.	[1] 20.5					
	Rotation and use of manure	26.8	7.9	10.6	74.5	19.3	18.9
	Rotation without manure	16.2					
	Use of manure without rotation.	[1] 18.9					
	Unlimed:						
	Rotation and use of chemical fertilizer.	31.7	11.2	17.6	63.6	20.2	24.5
	Rotation without chemical fertilizer.	14.1					
	Use of chemical fertilizer without rotation.	20.5					
	Rotation and use of manure	25.1	6.2	10.9	56.9	17.3	17.2
	Rotation without manure	14.2					
	Use of manure without rotation.	18.9					
Corn (Wooster)	Limed:						
	Rotation and use of chemical fertilizer.	54.5	20.4	23.4	87.2	38.2	41.0
	Rotation without chemical fertilizer.	31.1					
	Use of chemical fertilizer without rotation.	[1] 34.1					
	Rotation and use of manure	48.9	20.9	17.7	118.1	40.4	39.5
	Rotation without manure	31.2					
	Use of manure without rotation.	[1] 28.0					
	Unlimed:						
	Rotation and use of chemical fertilizer.	48.9	14.8	22.0	67.3	34.0	35.4
	Rotation without chemical fertilizer.	26.9					
	Use of chemical fertilizer without rotation.	34.1					
	Rotation and use of manure	44.2	16.2	17.2	94.2	36.2	34.8
	Rotation without manure	27.0					
	Use of manure without rotation.	28.0					
Oats (Wooster)	Limed:						
	Rotation and use of chemical fertilizer.	53.2	15.3	18.1	84.5	35.6	34.5
	Rotation without chemical fertilizer.	35.1					
	Use of chemical fertilizer without rotation.	[1] 37.9					
	Rotation and use of manure	44.0	15.6	8.4	185.7	25.4	24.7
	Rotation without manure	35.6					
	Use of manure without rotation.	[1] 28.4					
	Unlimed:						
	Rotation and use of chemical fertilizer.	52.8	14.9	20.5	72.7	32.8	34.1

[1] Yields are for unlimed plots in continuous culture.

TABLE 50.—*Comparison of relative values of rotation (R) and of the additive effects of conjoining rotation and the use of fertilizers on limed and unlimed soils*—Con.

Crop	Cultural conditions	Average yield per acre	Values for R and F: R	Values for R and F: F	Relative value of R	Additive effects of rotation and use of fertilizers: Sum of increase effected by rotation and use of fertilizer when practiced separately (r+f)	Additive effects of rotation and use of fertilizers: Actual increase effected by conjoining rotation and use of fertilizers
Oats (Wooster)	Unlimed—Continued.	*Bushels*	*Bushels*	*Bushels*	*Per cent*	*Bushels*	*Bushels*
	Rotation without chemical fertilizer.	32.3					
	Use of chemical fertilizer without rotation.	37.9					
	Rotation and use of manure	41.9	13.5	9.0	150.0	22.7	22.6
	Rotation without manure	32.9					
	Use of manure without rotation.	28.4					
Cotton (South Carolina).	Limed:	*Pounds*	*Pounds*	*Pounds*		*Pounds*	*Pounds*
	Rotation and use of chemical fertilizer.	1,929	69	345	20	1,014	714
	Rotation without chemical fertilizer.	1,584					
	Use of chemical fertilizer without rotation.	1,860					
	Unlimed:						
	Rotation and use of chemical fertilizer.	1,925	48	277	17.3	947	636
	Rotation without chemical fertilizer.	1,648					
	Use of chemical fertilizer without rotation.	1,877					

For the want of liming tests in the continuous-culture series at Wooster, the yields on the unlimed plots of the same series are used in evaluating rotation and the use of fertilizers on the limed plots in rotation. In doing so it is assumed that direct applications of lime on wheat, corn, and oats when grown in continuous culture produce no positive results. In as much as these three crops are tolerant of soil acidity, and for this reason show but little or no response to liming, the yields obtained on the unlimed plots in continuous culture can not deviate very much from the results if said plots were limed (*5*).

Because the comparable average yields are for different periods, the relative values for crop rotation in the Wooster experiments as given in Table 50 are higher than the corresponding values given in Table 35.

In comparing the results obtained under limed and unlimed conditions, as summarized in Table 50, it is to be noted that when the soil reaction is altered or changed by liming both the average absolute and relative values for rotation (*R*) have been increased—the average increase in the relative value, including all crops and fertilizers, being 23.0 per cent. These increases in the effectiveness of rotation due to liming are also reflected in the conjoint effects of rotation and the use of fertilizers, as indicated by the comparative values given in the last two subcolumns of the table.

The results of the long-continued liming tests herein recorded are few in number and hence inadequate in forming the basis of a general statement or principle; yet from a study of the data as summarized in Tables 47, 49, and especially 50, it would seem that, under the conditions of these experiments, the liming problem, with respect to productivity maintenance, is primarily a clover-rotation problem, and that the increases in the yields of such crops as wheat, corn, and oats

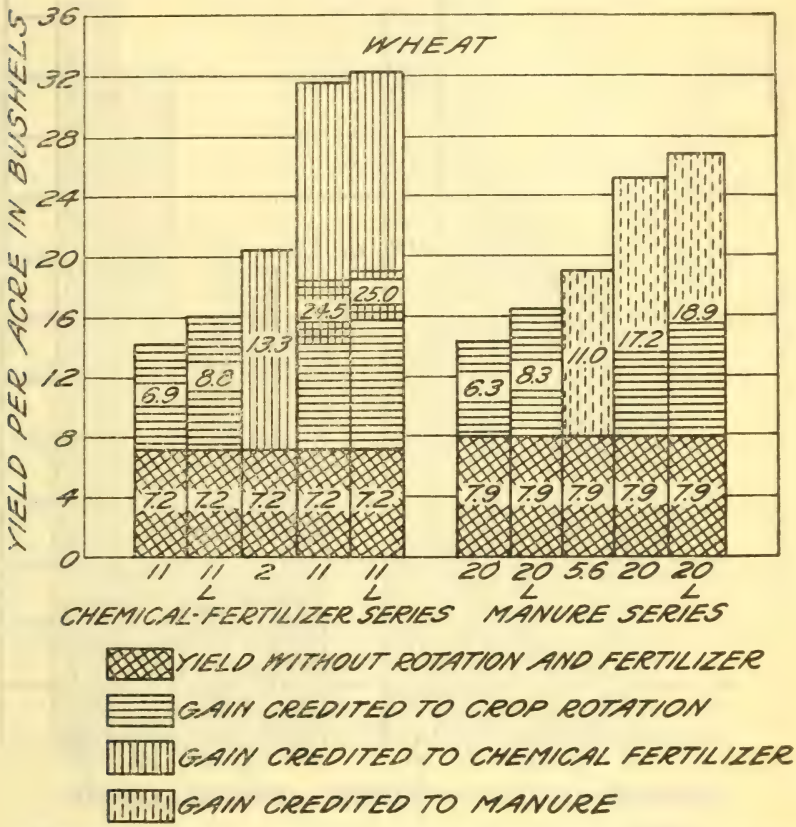

FIG. 7.—Chart visualizing the effects of soil reaction on the effectiveness of rotation and the use of fertilizer, as indicated by the yields of wheat at Wooster, Ohio. The plot numbers are given below each bar. L indicates the plots receiving lime. The horizontal-vertical crosshatching in each of the last two bars in the chemical-fertilizer series indicates (a) how much greater the actual increase effected by conjoining rotation and the use of fertilizer is than the sum of their separate increases, and (b) the unallocated increase effected by the interaction of rotation and the use of fertilizer

which may result when soil acidity is reduced or neutralized are due to indirect effects of liming.

In Figures 7, 8, 9, and 10 are visualized the results of the long-time liming tests herein described. In each case it is shown what proportion of the yield is credited to cultivation alone, the increase in yield effected by combining rotation or the use of fertilizers with cultivation, and the increase effected over cultivation by conjoining rotation and the use of fertilizers.

FIG. 8.—Chart showing the effects of soil reaction on the efficiency of rotation and the use of fertilizers, as indicated by the yields of corn at Wooster, Ohio. The plot numbers are given below the bars. L indicates the plots receiving lime. The unhachured space in each of the last two bars of the chemical-fertilizer series indicates how much greater the additive effects of conjoining rotation and the use of fertilizer are than the sum of the effects resulting when the two practices are acting independently of each other; or it may indicate to what extent the values of *R* and *F* overlap. The unhachured space in each of the last two bars in the manure series indicates to what extent the conjoint effects of rotation and the use of manure fall short of being fully additive. (Compare with Tables 49 and 50.)

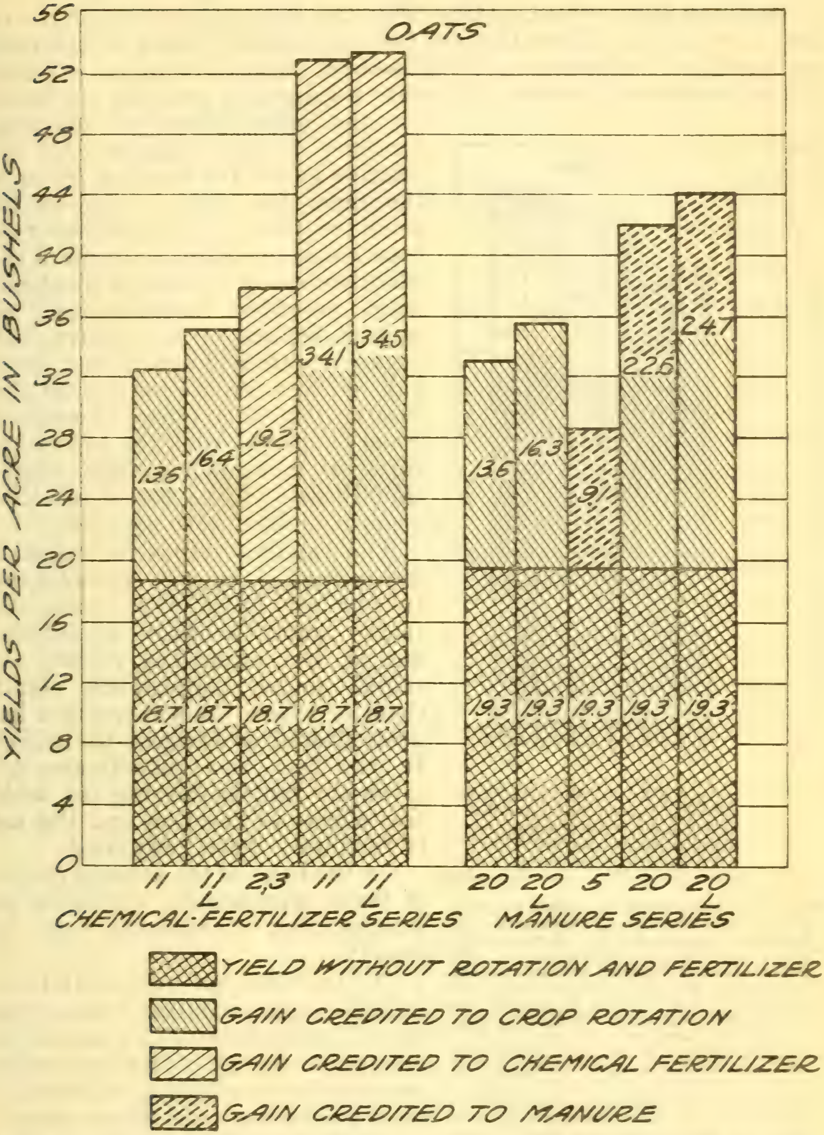

FIG. 9.—Chart showing the effects of soil reaction on the efficiency of rotation and the use of fertilizers, as indicated by the yields of oats at Wooster, Ohio. The plot numbers are indicated under the bars. L indicates the plots receiving lime. This shows what portion of each yield is credited to cultivation alone, the increase effected when to cultivation is added rotation or the use of fertilizers, and the total increase resulting when to cultivation are added the conjoint effects of rotation and the use of fertilizers. (Compare with data in Tables 49 and 50.)

SUMMARY OF RELATIVE VALUES OF CROP ROTATION AND OF CONJOINT EFFECTS OF ROTATION AND THE USE OF FERTILIZERS

A summary of the results thus far considered is given in Table 51. In studying the content of this table the following points are to be kept in mind: (1) All evaluations for rotation and the use of fertilizers are based on the increases in yields over cultivation alone or check plot in continuous culture; (2) relative values for rotation are based on the effectiveness of chemical fertilizer or stable manure; (3) the relative values for rotation given in the upper half of the table are for small *r*—that is, the efficiency of rotation as measured in terms of the effectiveness of the use of fertilizers when practiced independently of each other; and (4) the relative values for rotation given in the lower half of the table are for capital *R*—that is, the effectiveness of rotation when conjoined with the use of fertilizer as measured in terms of the effectiveness of the use of fertilizer when conjoined with rotation.

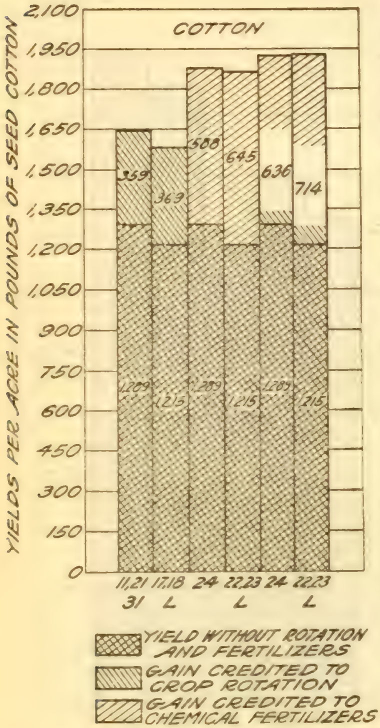

FIG. 10.—Chart showing the effects of soil reaction on the efficiency of crop rotation and the use of chemical fertilizer, as indicated by the yields of cotton at Florence, S. C. The plot numbers are indicated beneath the bars. L indicates the plots receiving lime. The unhachured space in each of the last two bars indicates the interactive effects of rotation and the use of fertilizer when one practice is conjoined with the other; and it shows also how much less the increase effected by the combined effects of rotation and fertilizers is than the sum of the gains resulting when rotation and the use of feritlizers are practiced independently of each other. (Compare with data in Tables 49 and 50.)

The relative values for rotation are arranged in two subcolumns. In one are given the values obtained under acid-soil conditions, and in the other the results obtained under nonacid-soil conditions or where the soil reaction has been altered or changed by liming. In the last two subcolumns are given the figures showing the additive effects of rotation and the use of fertilizers when conjoined.

On the basis of the average results of these experiments, the following summarizing statements may be made:

(1) Including all crops and all soils indicated, crop rotation without the use of fertilizers is 77.7 per cent as efficient as the use of fertilizers without rotation in effecting increases in crop yields over cultivation alone.

(2) Crop rotation, when added to cultivation and the use of fertilizers, is about 73 per cent as efficient as the use of fertilizers when added to cultivation and rotation, in effecting increases in crop yields.

(3) In general, crop rotation is practically 75 per cent as efficient as the use of fertilizer in effecting increases in crop yields as measured from the check-plot yields in continuous culture.

TABLE 51.—*Summary of the effects of crop rotation and of the use of fertilizers on crop yields*

ROTATION AND USE OF FERTILIZERS PRACTICED SEPARATELY

Crop	Station	Soil	Period of test (years inclusive)	Cultural conditions	Relative values for rotation: Soil acid in reaction	Relative values for rotation: Soil naturally supplied with lime or whose reaction has been altered or changed by liming	Additive effects of rotation and use of fertilizers: Sum of increases effected by rotation and use of fertilizers when practiced separately (r+f)	Additive effects of rotation and use of fertilizers: Actual increase effected by conjoining rotation and use of fertilizers
					Per cent	*Per cent*	*Bushels*	*Bushels*
Wheat	Rothamsted	Heavy loam on chalk	1851 to 1919	Rotation *v.* chemical fertilizer		104.2		
	Missouri	Putnam silt loam	1889 to 1918	do	54.7			
				Rotation *v.* manure	100.0			
	Wooster, Ohio	Wooster silt loam	1894 to 1918	Rotation *v.* chemical fertilizer	31.5			
				Rotation *v.* manure	37.0			
			1906 to 1918	Rotation *v.* chemical fertilizer	51.9			
				Rotation *v.* manure	57.3			
Corn	Missouri	Putnam silt loam	1889 to 1918	Rotation *v.* manure	102.7			
	Wooster, Ohio	Wooster silt loam	1894 to 1918	Rotation *v.* chemical fertilizer	54.5			
				Rotation *v.* manure	83.1			
			1900 to 1918	Rotation *v.* chemical fertilizer	65.0			
				Rotation *v.* manure	94.6			
	Illinois	Brown silt loam	1904 to 1916	Rotation *v.* fertilizer		302.2		
Oats	Missouri	Putnam silt loam	1889 to 1918	Rotation *v.* manure	53.0			
	Wooster, Ohio	Wooster silt loam	1894 to 1918	Rotation *v.* chemical fertilizer	60.4			
				Rotation *v.* manure	123.7			
			1901 and 1905 to 1918	Rotation *v.* chemical fertilizer	70.8			
				Rotation *v.* manure	149.5			
Barley	Rothamsted	Heavy loam on chalk	1853 to 1921	Rotation *v.* chemical fertilizer		27.9		
Cotton	South Carolina	Orangeburg very fine sandy loam.	1914 to 1919	do	[1] 60.6 61.1	57.2		
Tobacco	Germantown, Ohio	Miami clay loam	1903 to 1918	do		28.3		
				Rotation *v.* manure		32.8		

ROTATION AND USE OF FERTILIZERS CONJOINED

Crop	Station	Soil	Period of test (years inclusive)	Cultural conditions	Soil acid in reaction	Soil naturally supplied with lime or whose reaction has been altered or changed by liming	Sum of increases (r+f)	Actual increase
Wheat	Rothamsted	Heavy loam on chalk	1851 to 1919	Rotation *v.* chemical fertilizer		105.6	22.97	20.16
	Missouri	Putnam silt loam	1889 to 1918	do	36.4		21.5	17.5
				Rotation *v.* manure	100.0		20.0	19.1

[1] Top figure is relative value based on the average of the yields obtained on unlimed plots 24, 27, and 30. (See Table 42.)

TABLE 51.—*Summary of the effects of crop rotation and of the use of fertilizers on crop yields*—Continued

ROTATION AND USE OF FERTILIZERS CONJOINED—Continued

Crop	Station	Soil	Period of test (years inclusive)	Cultural conditions	Relative values for rotation: Soil acid in reaction	Relative values for rotation: Soil naturally supplied with lime or whose reaction has been altered or changed by liming	Additive effects of rotation and use of fertilizers: Sum of increases effected by rotation and use of fertilizers when practiced separately (r+f)	Additive effects of rotation and use of fertilizers: Actual increase effected by conjoining rotation and use of fertilizers
Wheat—Contd.					*Per cent*	*Per cent*	*Bushels*	*Bushels*
	Wooster, Ohio	Wooster silt loam	1894 to 1918	Rotation *v.* chemical fertilizer	50.5	----------	15.74	20.35
				Rotation *v.* manure	37.2	----------	11.48	11.51
			1906 to 1918	Rotation *v.* chemical fertilizer	63.6	72.2	20.2	24.5
							[1] (L) 22.1	(L) 25.0
				Rotation *v.* manure	56.9	74.5	17.3	17.2
							(L) 19.3	(L) 18.9
Corn	Missouri	Putnam silt loam	1889 to 1918	do	103.9	----------	29.8	25.3
	Wooster, Ohio	Wooster silt loam	1894 to 1918	Rotation *v.* chemical fertilizer	55.4	----------	29.36	29.72
				Rotation *v.* manure	80.8	----------	31.49	29.48
			1900 to 1918	Rotation *v.* chemical fertilizer	67.3	87.2	34.0	35.4
							(L) 38.2	(L) 41.0
				Rotation *v.* manure	94.2	118.1	36.2	34.8
							(L) 40.4	(L) 39.5
Oats	Illinois	Brown silt loam	1904 to 1916	Rotation *v.* fertilizer	----------	213.4	37.0	44.2
	Missouri	Putnam silt loam	1889 to 1918	Rotation *v.* manure	33.7	----------	17.8	14.5
	Wooster, Ohio	Wooster silt loam	1894 to 1918	Rotation *v.* chemical fertilizer	62.5	----------	29.37	30.38
				Rotation *v.* manure	124.9	----------	18.19	17.80
			1901 and 1905 to 1918	Rotation *v.* chemical fertilizer	72.7	84.5	32.8	34.1
							(L) 35.6	(L) 34.5
				Rotation *v.* manure	150.0	185.7	22.7	22.6
							(L) 25.4	(L) 24.7
Barley	Rothamsted	Heavy loam on chalk	1853 to 1921	Rotation *v.* chemical fertilizer	----------	−49.2	35.58	21.21
							Pounds	*Pounds*
Cotton	South Carolina	Orangeburg very fine sandy loam	1914 to 1919	do	24.7	----------	795	559
					17.3	20.0	947	636
							(L) 1,014	(L) 714
Tobacco	Germantown, Ohio	Miami clay loam	1903 to 1918	do	----------	12.5	966	830
				Rotation *v.* manure	----------	24.6	717	658

[1] (L) indicates additive effects on soils that have been limed.

(4) In general, crop rotation is nearly 90 per cent as efficient as the use of fertilizer in effecting increases in the yields of wheat, corn, and oats, above check-plot yields in continuous culture.

(5) Considering values based on comparable results, the average relative value of crop rotation is higher when it is based on the effectiveness of stable manure than when based on the use of chemical fertilizers—being 67 per cent greater under conditions when rotation and the use of fertilizer are practiced apart from each other and nearly 58 per cent greater under conditions when one practice is conjoined with the other. This indicates that larger increases in crop yields have been effected by the applications of chemical fertilizer made on the experimental plots than by the applications of manure.

(6) Excluding clover, timothy, and cowpeas, the average relative value of rotation is practically 20 per cent higher on soils whose reactions have been altered or changed by liming, than on acid soils.

(7) Except in case of barley at Rothamsted, the conjoint effects of rotation and the use of fertilizers are additive—being often more than fully additive.

VALUE OF CROP ROTATION AND OF THE USE OF FERTILIZERS IN MAINTAINING AND INCREASING SOIL PRODUCTIVITY

Thus far in this study, crop-rotation values have been calculated from the differences in yields obtained on fertilized and unfertilized plots in continuous culture and in rotation—in each case the increases over the yields in continuous culture being the basis for calculation. The discussion which follows is of rotation and fertilizer values considered from the points of view of maintaining and increasing soil productivity under the conditions of the same experiments described in foregoing paragraphs.

This second method, as stated before, necessitates the determining of the natural producing power of the soil at the beginning of each experiment, which is termed the *maintenance yield*. This yield is taken as the basis from which are calculated the values for crop rotation and the use of fertilizers in maintaining and increasing soil productivity.

It was thought best to determine the maintenance yield in each case by taking the 5-year average at the beginning of the test or before the experiment was begun.

MAINTAINING SOIL PRODUCTIVITY

In Table 52 are summarized the data concerning the relative value of crop rotation in maintaining soil productivity, as based on the data given in the foregoing tables. In the fifth column are given, in each case, the years selected for the 5-year average—these being considered the best that can be obtained from the data given in the publications previously referred to. The South Carolina experiments are omitted from the table, because they cover only a short period; and the experiments on tobacco at Germantown, Ohio, are omitted because the annual yields at the beginning of the experiment do not appear to have been published.

TABLE 52.—*Relative value of crop rotation in maintaining soil productivity*

Crop	Station	Kind of fertilizer used	Period of experiment covered by study (years inclusive)	Average yield at beginning of test—maintenance yield: Years selected for 5-year average	Average yield at beginning of test—maintenance yield: Five-year average maintenance yield	Average yield for rotation alone	Average yield for use of fertilizer alone	Relative value for crop rotation, as compared with fertilizers, in maintaining soil productivity
					Bushels	*Bushels*	*Bushels*	*Per cent*
Wheat	Rothamsted	Chemical fertilizer	1851–1921	1846–1850	17.5	24.1	23.6	102.2
	Columbia, Mo.	do	1895–1918	[1] 1889–1894	14.2	22.8	27.6	82.6
		Manure	1895–1918	1889–1894	14.2	20.1	20.1	100.0
	Wooster, Ohio	Chemical fertilizer	1899–1918	1894–1898	10.5	12.0	19.7	60.9
		Manure	1899–1918	1894–1898	10.1	12.1	17.1	70.8
Corn	Columbia, Mo.	do	1894–1918	1889–1893	33.5	39.3	33.8	116.2
	Wooster, Ohio	Chemical fertilizer	1899–1918	1894–1898	29.0	26.4	34.4	[2] 76.7
		Manure	1899–1918	1894–1898	27.2	26.6	28.2	94.3
	Urbana, Ill.	Phosphates and manure.	1904–1916	1899–1903	41.6	51.2	32.6	[3] 157.1
Oats	Columbia, Mo.	Manure	1895–1918	[1] 1889–1894	23.6	28.9	34.2	84.5
	Wooster, Ohio	Chemical fertilizer	1899–1918	1894–1898	27.8	32.2	38.8	83.0
		Manure	1899–1918	1894–1898	28.4	32.3	29.6	109.1
Barley	Rothamsted	Chemical fertilizer	1857–1921	1852–1856	27.4	21.0	42.0	[4] 50.0

[1] Yield for 1 year is omitted, and 1 year the crop failed.
[2] Average yield on check plot in continuous culture is 13.3 bushels.
[3] Average yield on check plot in continuous culture is 23.4 bushels.
[4] Average yield on check plot in continuous culture is 14.1 bushels.

In the table it is to be noted that, under the conditions of the experiments considered, crop rotation without the use of fertilizer maintained the producing power of the soil, except in the case of corn at Wooster and of barley at Rothamsted, and the use of fertilizer without rotation maintained the producing power of the soil, except in the case of corn at Urbana.

INCREASING SOIL PRODUCTIVITY

In Table 53 is given a summary of data calculated from previous tables, showing the relative value for crop rotation (*r*) and the conjoint effects of rotation and the use of fertilizers in increasing soil productivity.

TABLE 53.—*Relative value of rotation (r) and the conjoint effects of rotation and the use of fertilizers in increasing soil productivity*

Crop	Station	Kind of fertilizer	Maintenance yield	Increase [1] in productivity (over maintenance yield) effected by—		Relative value for rotation (*r*) as compared with fertilizers in increasing soil productivity	Average yield, rotation conjoined with use of fertilizer	Additive effects of rotation and use of fertilizers	
				Rotation	Use of fertilizer			Sum of increase of productivity effected by rotation and use of fertilizer when practiced separately (*r*+*f*)	Actual increase in productivity effected by conjoint action of rotation and use of fertilizer
			Bushels	*Bushels*	*Bushels*	*Per cent*	*Bushels*	*Bushels*	*Bushels*
Wheat	Rothamsted	Chemical fertilizer	17.5	6.6	6.1	108.2	32.5	12.7	15.0
	Columbia, Mo.	do	14.2	8.6	13.4	64.2	32.5	22.0	18.3
	do	Stable manure	14.2	5.9	5.9	100.0	30.6	11.8	16.4
	Wooster, Ohio	Chemical fertilizer	10.5	1.5	9.2	16.3	30.0	10.7	19.5
	Wooster, Ohio	Manure	10.1	2.0	7.0	28.6	21.7	9.0	11.6
Corn	Columbia, Mo.	do	33.5	5.5	0.3	....	48.9	5.8	15.4
	Wooster, Ohio	Chemical fertilizer	29.0	−2.6	5.4	....	47.9	2.8	18.9
	Wooster, Ohio	Manure	27.2	−0.6	1.0	....	43.8	0.4	16.6
	Illinois	Phosphate and manure.	41.6	9.6	−9.0	....	67.6	0.6	26.0
Oats	Columbia, Mo.	Manure	23.6	5.3	10.6	50.0	37.5	15.9	13.9
	Wooster, Ohio	Chemical fertilizer	27.8	4.4	11.0	40.0	53.2	15.4	25.4
	Wooster, Ohio	Manure	28.4	3.9	1.2	325.0	41.3	5.1	12.9
Barley	Rothamsted	Chemical fertilizer	27.4	−6.4	14.6	....	35.0	8.2	7.6

[1] Increases above maintenance yield effected by rotation and the use of fertilizer when practiced independently of each other.

It is to be observed that, in 8 of the 13 experiments listed, the use of chemical fertilizer or manure, when practiced in the absence of rotation, is more effective in increasing productivity than rotation alone; and in 5 cases the effectiveness of rotation is equal to or greater than that of the use of fertilizer. And further, in all cases, except the barley test, the conjoint effects of rotation and the use of fertilizer are additive in increasing soil fertility—in 10 of the experiments the effects being *more than fully additive*.

EFFECT OF SOIL REACTION ON ROTATION AND USE OF FERTILIZERS

It may be of interest to summarize the effects of soil reaction on the conjoint action of rotation and the use of fertilizer in increasing fertility. In such a study only the results obtained on wheat, corn, and oats at Wooster are available. This summary is given in Table 54.

TABLE 54.—*Effect of soil reaction on the conjoint effect of rotation and of the use of fertilizers in increasing soil productivity, Wooster, Ohio*

Crop	Kind of fertilizer used	Period of experiment covered by study	Maintenance yield: Years selected for 5-year average[1]	Maintenance yield: 5-year average	Average yield, rotation conjoined with use of fertilizer	Additive effects of rotation and use of fertilizers: Sum of increases in productivity effected by rotation and use of fertilizer when practiced separately (r+f)	Additive effects of rotation and use of fertilizers: Actual increase in productivity effected by conjoint action of rotation and use of fertilizer
LIMED SOIL							
				Bushels	*Bushels*	*Bushels*	*Bushels*
Wheat	Chemical fertilizer	1906–1918	1901–1905	8.5	32.2	19.5	23.7
	Manure	1906–1918	1901–1905	9.1	26.8	16.7	16.7
Corn	Chemical fertilizer	1900–1918	1895–1899	29.6	54.5	6.0	24.6
	Manure	1900–1918	1895–1899	27.2	48.9	4.8	21.7
Oats	Chemical fertilizer	1901, 1905–1918	1900–1904	19.5	53.2	34.0	33.7
	Manure	1901, 1905–1918	1900–1904	21.6	44.0	20.8	22.4
UNLIMED SOIL							
Wheat	Chemical fertilizer	1906–1918	1901–1905	8.5	31.7	17.6	23.2
	Manure	1906–1918	1901–1905	9.1	25.1	14.9	16.0
Corn	Chemical fertilizer	1900–1918	1895–1899	29.6	48.9	1.4	19.3
	Manure	1900–1918	1895–1899	27.2	44.2	0.6	17.0
Oats	Chemical fertilizer	1901, 1905–1918	1900–1904	19.5	52.8	31.2	33.3
	Manure	1901, 1905–1918	1900–1904	21.6	41.9	18.1	20.3

[1] 5-year average based on yields given in Tables 30 and 32.

Here it is to be observed that only in the case of corn does lime effect an increase exceeding 3 bushels per acre from the conjoint action of rotation and the use of fertilizer. However, it may be concluded that changing or altering the soil reaction by liming tends to increase the conjoint effectiveness of rotation and fertilizers.

GENERAL DISCUSSION

Two methods have been employed in evaluating the effectiveness of rotation in crop production, and in determining the additive effects of rotation and the use of fertilizers when these two farm practices are conjoined. Although in one method the evaluations are based on the increases over the yields obtained on check plots in continuous culture and in rotation, and in the second method, on the increases over the maintenance yield, or the average yield obtained at the beginning of the experiments, yet the general results as regards the value of rotation in relation to soil productivity all point in the same direction.

The evaluation of crop rotation as calculated from the maintenance yield seems to be the more logical and scientific method, especially from the point of view of maintaining and increasing the producing power of the soil. However, in determining the values for rotation and the use of fertilizer when one practice is combined with the other, or in determining the relative value of *R*, the first method referred to above has been found to be very useful.

Taking all the results into consideration, as based on the average results of the published data of the long-time fertility experiments herein considered, the following important facts as regards the value of crop rotation have been brought out:

(1) Rotation of crops is practically 75 per cent as effective as the use of fertilizer in effecting increases in crop yields—being nearly 90 per cent as effective as the use of fertilizer when the results on wheat, corn, and oats, only, are considered.

(2) As based on the average yields at the beginning of the experiments involving fully comparable yields, rotation has been shown to be 91.5 per cent as effective as the use of fertilizer in maintaining the producing power of the soil.

(3) In increasing soil productivity, the effects of rotation alone may equal or exceed the effects of the use of fertilizer without rotation.

(4) The effects of rotation and the use of fertilizer apparently are not the same, as is shown by the fact that their conjoint effects on crop yields are additive—being more than fully additive in most of the cases considered.

(5) In permanent crop production, high productivity levels are possible only when rotation and the use of fertilizer are conjoined.

It is not the object of this study to emphasize primarily the important place that fertilizers assume in permanent soil productivity, the value of which is fully recognized; but rather to stress the importance of crop rotation in relation to profitable crop production and to show the necessity of conjoining rotation and the use of fertilizers in the establishment of permanent agriculture. No attempt will be made in this discussion to formulate any rules for the use of fertilizers for greater efficiency; but attention is directed (1) to some of the conditions under which these experiments are conducted; (2) to a reasonable interpretation of the above facts in relation to the Nation's food-production problem; and (3) to a practical application of the principles involved to efficient and profitable soil management.

In all the fertility tests included in this study the experimental plans are rigid or fixed, there being no modification whatever in the rotation involved in any particular experiment, and but little or no alteration is made in the fertilizers applied. Of course, in the long-continued fertility tests, rigidity of plans is generally accepted as necessary; but in practical experience the farmer usually adopts more or less flexible plans. He may alter or even change the rotation, if necessary, or he may vary the fertilizer treatment to better meet the soil and crop requirements, or he may lime the soil only when crop or soil conditions indicate the necessity of liming. A study of the soil-management methods practiced by successful and leading farmers, especially in the older farming sections, clearly shows that the maintenance of soil productivity is accomplished most efficiently, not by rigid or fixed systems of cropping, fertilizing, and liming, but by systems that are more or less flexible. In rational farming, soil, crop, topographic and economic conditions on probably the majority of farms compel variations in rotations and in the use of soil-improvement materials. In fact, because of these conditions, there are only a comparatively few farms, taking the country at large, which can be successfully divided into a certain number of fields or cropping units to accommodate a single, fixed rotation.[3] This is quite evident, for uniformity of soil as regards kind or producing power is rather unusual. A rotation best suited for a field of low-producing sand is seldom suited to a field of productive silt loam; a hillside field subject to soil erosion calls for a different management as regards rotation than a field on a flat area; and so on.

The primary question that confronts a practical farmer who farms more or less with livestock does not concern rotation so much as it does the acreage of crops necessary to best meet his feeding requirements. On the other hand, the truck grower is concerned primarily with the question of the crops best suited to meet the market conditions. In either case the cropping problem resolves itself into two parts: (1) The growing of the desired crops in a manner, or in different rotations, best suited to the soil and crop conditions, and, (2) the dove-tailing, so to speak, of the different rotations so as to enable the farmer to realize annually the required acreage of each crop he desires to grow.

In the light of economic and rational fertilizer practice, the applications of chemical fertilizers made on the experimental plots are to be regarded as heavy or excessive, and the fertilizers in themselves "unbalanced." Nevertheless, the applications selected for comparable yields have given, in the majority of cases, most favorable results. Over against the effects of these heavy applications have been weighed the effects of fixed rotations, whose effects in any particular test can not be regarded as being determined by material quantity, as in case of the fertilizers.

It is not possible to know with any degree of certainty what the results would have been if, in some of the experiments, the rotation had been altered or changed, or if in all the experiments the applications of chemical fertilizer were modified to conform to the modern ideas of fertilizer practice, which are generally recognized as being the more scientific. That such modifications, or breaks in the rigidity of the experimental plans, would have resulted in higher average yields seems quite certain, for the higher average yields obtained by leading farmers carry considerable significance.

The average yield of wheat on the fertilized plot 2–C, in rotation on the Agdell field at Rothamsted, for example, is 32.5 bushels, while the average yield for England and Wales is 31.7 bushels (*16, p. 56*). This means that the average yield of wheat on many farms in England and Wales must be much higher than that on the Agdell field; and the chances are that these high yields are not obtained as

[3] A fixed rotation may be defined as a rotation in which the crops recur at regular intervals and which occupies a fixed number of years; for example, a four-year rotation of corn, oats, wheat, and clover.

the result of any such rigid rotation and fertilization systems as are practiced on the Agdell field.

This discussion of rotation assumes diversification in cropping. Statistics show that cotton, corn, wheat, oats, and hay each occupies more than 30,000,000 acres on American farms. Together these five crops occupy 87.5 per cent of the total crop area of the country (*17, p. 2*). It is out of the question to discuss the value of rotation in relation to permanent productivity from the point of view of a rotation that is suitable for all sections of the country, because it is evident that a 5-year rotation including the five major crops is impossible in a country so large and with such wide differences in climatic and agricultural conditions. However, a study of the distribution of the important crops grown in the agricultural regions of the United States, within the several States, and within smaller areas or districts, will show that flexible rotations [4] are possible in most sections or localities or on most farms, the possible exceptions being on specialized, 1-crop farms and in certain dry-land farming sections where, because of scant rainfall, a change from a 1-crop system, as from wheat and fallow, is practically impossible or economically hazardous.

As regards chemical or commercial fertilizers, their use is becoming more and more general, this being the natural outcome as virgin, arable soils are kept longer and longer under cultivation. The richer the soil and the more skillful the farmer in his soil management, the longer virgin soils can produce profitable crops without the use of fertilizers. History shows, however, that sooner or later exhaustive cropping brings the best of virgin soils to a point where the use of manure or some other form of fertilizer becomes necessary for the realization of profitable yields.

In the light of this study it may well be assumed that on productive, virgin soils a good rotation may for years prove more effective in maintaining yields than manure or single, mixed, or even complete commercial fertilizers. In time, however, the fertilizers give more and more positive results, until they approach the effectiveness of rotation, as the experiments on corn at Urbana, Ill., seem to show.

Cultivation in fertility maintenance, especially as regards the preparation of the seed bed, is generally recognized as fundamental, regardless of soil, climate, or economic conditions.

In this brief survey directing attention to the general importance of crop rotation, the use of fertilizers, and cultivation, it must be recognized that on these three practices, mainly, the maintenance of soil productivity generally depends. The relative importance of each practice will necessarily vary on the various farms or soils, their relative efficiencies being determined by such factors as the quality of the soil, the character of the rotation, and the kind and quantity of fertilizers used. When conditions are such as to cause cultivation, rotation, and the use of fertilizer all to become positively effective, the resultant yields may be regarded as consisting of three parts, one portion representing the effectiveness of cultivation alone, a second portion to be credited to the effects of rotation, and a third portion representing the effectiveness of fertilizers. Thus, assuming

[4] A flexible rotation may be defined as a rotation in which different kinds of crops, such as intertilled small-grain, and hay or legume crops, follow in definite order as named, but in which the number of years of growing the specific crops is not fixed.

a 1-crop system of farming, the average crop yields of a farm or community or of the whole country can be greatly increased if to cultivation is added crop rotation, and can be further increased if to cultivation and rotation, in turn, is added the use of fertilizers.

If conditions were such as to make possible the application of so simple a productivity program, the food-production problem of the Nation would not prove a serious one for many years to come. The general conditions as they exist, however, call for a very different interpretation or application of the facts brought forth as a result of this study.

Cultivation is generally practiced. Rotation of some description is practiced by most farmers, though the rotation may consist in merely a change of crops without any definite system or any degree of regularity. Manure, wherever it is produced, is usually disposed of for the good of the land; and commercial fertilizers are coming more and more into use, either specially in single or incomplete forms to correct certain soil deficiencies or to meet the requirements of special crops, or generally in mixed or complete forms.

From the point of view of the country at large, any increase in the average crop yields as effected by cultivation is possible only when a general improvement is made in tillage methods or practices. Such effects can be realized only to the extent that each individual farmer masters the fundamental principles of tillage and studies his soils, crops, and machinery so as to enable him to make the proper application of the tillage principles to the conditions on his farm through the means at his command.

Farm manure and commercial fertilizers seem to be regarded as possessing the greatest possibilities with reference to maintaining soil productivity and in effecting increases in crop yields. Judging from the experiences of farmers who have used such materials as dung, seaweed ashes, wood ashes, street refuse, and certain kinds of marl during pre-Roman and Roman times, and from the profound effects that manufactured or commercial fertilizers have had, since 1840, on the agriculture of the leading nations of the world, the basis for the recognition of great possibilities in fertilizers is well grounded.

Generally speaking, over against the great possibilities of the use of fertilizers in maintaining and increasing soil productivity are to be placed the possibilities of crop rotation, which have been found to exceed very often those of the use of manure or chemical fertilizers. Though it is true that most farmers alternate their crops in one manner or another, the maximum effects of crop rotation certainly are not reflected in the average crop yields of the agricultural regions of the United States, or of the United States as a whole. There can be little doubt that rotation can be made much more effective in increasing as well as in maintaining crop yields, not only in sections in which fertilizer practices have become more or less permanently established, but as well in sections in which commercial fertilizers are sparingly used, or are still practically unknown.

Since it has been found that rigid or fixed rotations are very often more effective than the use of fertilizers in increasing the yields of such crops as wheat, corn, and oats, it seems reasonable to assume that properly planned, flexible rotations would prove even more effective in practical farming, both from the productivity and economic points of view.

GENERAL SUMMARY AND CONCLUSIONS

This bulletin reviews a study of the effects of crop rotation and the use of fertilizers on the yields of crops, the primary objects being (1) to determine some definite measure of the value of crop rotation in crop production and (2) to compare the beneficial effects of rotation with those of the use of manure and complete chemical fertilizers in maintaining and increasing soil productivity.

The maintenance of soil productivity depends in a large measure on three factors commonly referred to as farm practices: (1) Cultivation of the soil, (2) rotation of crops, and (3) the use of fertilizers.

Three methods of study are suggested. One is discarded because of the assumptions involved; the other two methods, which are accepted, are fully explained (pp. 3–10).

The effects of crop rotation and the use of fertilizers on crop yields, as determined by the first mehod, in which evaluations are based on increases over the yields in continuous culture and rotation alone, are as follows:

Results of 72 years on wheat at Rothamsted, England, show that, under the conditions of these experiments, crop rotation without fertilizers is somewhat more effective than the use of a heavy application of complete chemical fertilizer; whereas, in case of barley, rotation is a little less than 28 per cent as effective as the use of fertilizer. And further, rotation, when added to the use of fertilizer, is 105.6 per cent as effective as the use of fertilizer when added to rotation; in other words, the relative value of rotation is 105.6 per cent. When rotation and the use of fertilizer are conjoined, the effects on the yields of wheat are somewhat less than fully additive; in the case of barley their conjoint effects are not additive (pp. 10–18).

Under the conditions of the experiment at Columbia, Mo. (results for 30 years), the relative values of rotation alone, as based on the effectiveness of the use of fertilizer when practiced in the absence of rotation, are as follows: On wheat, corn, and oats, when fertilized with farm manure, 100 per cent, 102.7 per cent, and 53 per cent, respectively; and on wheat fertilized with complete chemical fertilizer, 54.7 per cent. When one practice is added to the other, the relative values for rotation in the manure series are as follows: Wheat, 100 per cent; corn, 103.9 per cent; and oats, 33.7 per cent; and on wheat fertilized with chemical fertilizer, 36.4 per cent. When rotation and the use of fertilizer are conjoined their combined effects on crop yields in each case are somewhat less than fully additive (pp. 18–29).

The tests at Wooster, Ohio, as reported for 25 years, show the relative values for rotation alone, as follows: On wheat, corn, and oats in the chemical-fertilizer series, 31.5 per cent, 54.5 per cent, and 60.4 per cent, respectively; and on the same crops in the manure series, 37 per cent, 83.1 per cent, and 123.7 per cent, respectively. When one practice is added to the other, the relative values for rotation are as follows: On wheat, corn, and oats in the chemical-fertilizer series, 50.5 per cent, 55.4 per cent, and 62.5 per cent, respectively, and on the same crops in the manure series, 37.2 per cent, 80.8 per cent, and 124.9 per cent, respectively. When rotation and the use of fertilizers are conjoined the effects on crop yields are practically fully additive, except in case of the use of chemical fertilizer on wheat, where the conjoint effects are more than fully additive (pp. 29–38).

Under the conditions of the 16-year tests on tobacco at Germantown, Ohio, crop rotation is from 12.5 per cent to 28.3 per cent as effective as the use of chemical fertilizer and about 33 per cent as effective as the use of a 10-ton application of manure. When rotation and the use of fertilizer are combined, their effects are somewhat less than fully additive (pp. 38–39).

Under the conditions of the experiments on brown silt loam at Urbana, Ill., results for 14 years show that crop rotation without fertilizer is 302.2 per cent as efficient as the combined use of manure, phosphate, and lime without rotation in effecting increases in the yield of corn (over check plot in continuous culture). When rotation is added to the use of fertilizers, the increase effected is 113.4 per cent greater than when the use of fertilizers is added to rotation. When rotation and the use of fertilizers are conjoined their combined effects in increasing the yield of corn are more than fully additive (pp. 39–41).

The 6-year results on cotton at Florence, S. C., show that rotation without fertilizers is 60.6 per cent as effective as the use of chemical fertilizer without rotation. When one practice is conjoined with the other, rotation is only about 25 per cent as effective as the use of fertilizer in effecting increases in yield. Under the conditions of these experiments the combined effects of rotation and fertilizer are less than fully additive (pp. 41–44).

The nature of the liming tests at Wooster, Ohio, and at Florence, S. C., made it possible to study the effect of soil reaction on the effects of crop rotation and the use of fertilizers in effecting increases in the yields of wheat, Indian corn, and oats (Wooster), and of cotton (South Carolina). These experiments show that an alteration or change in the soil reaction as effected by liming has increased the absolute and relative values for rotation when conjoined with the use of fertilizers—the average increase in the relative values over unlimed conditions being 23 per cent. This increase in the relative value for rotation due to liming is reflected in the increased additive effects when, on limed soils, rotation and the use of fertilizers are conjoined (pp. 44–54).

If these long-time tests are typical of results showing the effects of liming, it would seem that the liming problem is primarily a clover-rotation problem (pp. 51–54).

Summary of foregoing results:

(1) Including all crops and all soils considered, crop rotation is practically 75 per cent as efficient as the use of fertilizer in effecting increases in crop yields.

(2) In general, crop rotation is nearly 90 per cent as efficient as the use of fertilizer in effecting increases in the yields of wheat, corn, and oats.

(3) Excluding such crops as clover, timothy, and cowpeas, the average relative effectiveness of rotation is practically 20 per cent higher on soils whose reactions have been altered or changed by liming, than on acid soils.

(4) Except in case of barley at Rothamsted, the conjoint effects of rotation and the use of fertilizers on crop yields are additive—being often more than fully additive (pp. 55–56).

When rotation evaluations are based on the maintenance yields or the average yields obtained at the beginning of the experiments according to the second method of study, results show that both crop rotation without the use of fertilizers and the use of fertilizers without rotation maintained the producing power of the soil, except in a few cases (pp. 57-58).

In 5 of the 13 experiments considered, crop rotation without fertilizers is equally or more effective than the use of fertilizer without rotation in increasing soil productivity. In the other 8 experiments it is shown that the use of fertilizer is the more effective. And further, in all cases, except the barley experiment at Rothamsted, the conjoint effects of rotation and the use of fertilizer are additive in effecting increases in soil productivity—in 10 of the experiments the effects being more than fully additive (pp. 59-60).

The following facts concerning the value of crop rotation summarize all the results arrived at from both methods of study:

(1) Rotation of crops, when practiced with and without the use of fertilizer, averages 75 per cent as effective as the use of fertilizer, in effecting increases in crop yields, or 90 per cent as effective as fertilizers when the results on wheat, corn, and oats, only are averaged.

(2) In most cases, as determined by the conditions of the experiments considered, it has been found that rotation is 91.5 per cent as effective as the use of fertilizer in maintaining the producing power of the soil.

(3) In increasing soil productivity, as measured from the maintenance yields, the effects of rotation alone have been found, at times, to equal or exceed the effects of the use of fertilizers.

(4) The conjoint effects of rotation and the use of fertilizers are additive, as effecting increases in yields over the check plots in continuous culture and rotation; or as effecting increases in soil productivity, when measured by increases above the maintenance yields.

(5) Altering or changing the acid reaction of a soil by liming increases the relative effectiveness of crop rotation.

(6) On soils long under cultivation, highest yields are possible only when rotation of crops and the use of fertilizers are conjoined.

The above facts point to the following principles of permanent soil productivity:

(1) Crop rotation is so important a farm practice, especially in maintaining and increasing the yields of cereal crops, that its effectiveness may often equal or even exceed the effectiveness of the use of complete chemical fertilizer or farm manure.

(2) The conjoint effects of crop rotation and the use of fertilizers are additive, as effecting increases in crop yields.

(3) The relative efficiency of crop rotation is greater on soils naturally supplied with lime or on soils whose reactions have been altered or changed by liming than on soils that are acid in character.

LITERATURE CITED

(1) Blackwell, C. P., and Buie, T. S.
S. C. Agri. Exper. Sta. Bull. 209.

(2) Columella, Lucius Junius Moderatus.
Of Husbandry, in Twelve Books; and his book Concerning Trees, English translation, London, 1745.

(3) Gardner, F. D., Noll, C. F., and Lewis, R. D.
Pa. Agr. Exper. Sta. Bull. 175, 1922.

(4) Hall, A. D.
The Book of the Rothamsted Experiments, second edition.

(5) Hartwell, B. L., and Damon, S. C.
R. I. Agr. Exper. Sta. Bull. 160.

(6) Hopkins, C. G., Garrett, F. W., Whitchurch, J. E., and Fahrnkopf, H. F.
Univ. of Ill. Agr. Exper. Sta. Bull. 219, 1919.

(7) Hutchinson, H. B., and Miller, N. H. J.
Direct Assimilation of Ammonium by Plants. Rothamsted Memoir, Vol. VIII.

(8) Lawes and Gilbert.
Rothamsted Memoirs, Vol. V, Fertility.

(9) ——— ———
The Rothamsted Experiments, over 50 years.

(10) Miller and Krusekopf.
Manual of the Principal Soils of Missouri, Mo. Agr. Exper. Sta., 1921.

(11) Miller, M. F., and Hudelson, R. R.
Mo. Agr. Exper. Sta. Bull. 182, 1921.

(12) Ohio Agr. Exper. Sta.
Bull. 336, 1919.

(13) Ohio Agr. Exper. Sta. publications.
Bulletins, Nos. 184 and 336.
Circulars, Nos. 83, 92, 104, 114, 120, 131, and 144.

(14) Prothero, R. E.
English Farming Past and Present, 1917.

(15) Rothamsted Experiment Station publications.
(*a*) Lawes and Gilbert, Rothamsted Memoirs, Vol. III.
(*b*) Lawes and Gilbert, The Rothamsted Experiments, over 50 years, 1895.
(*c*) Memoranda of the Plan and Results of the Rothamsted Field Results, 1855–1889.
(*d*) Memoranda of the Origin, Plan and Results of the Field and Other Experiments at Rothamsted, 1899–1901.
(*e*) The Rothamsted Field Experiments, Plans and Summary Tables, 1896–1905.
(*f*) Rothamsted Experiment Station, Guide to Experimental Plots, 1906, 1913.
(*g*) Rothamsted Experimental Station, Annual Supplement to Guide to the Experimental Plots, 1906 ,1907.
(*h*) Rothamsted Experimental Station, Annual Report, with the Supplement to the Guide to the Experiment Plots, 1908–1922.

(16) ———
Report 1921–22.

(17) Spillman, W. J.
Distribution of Types of Farming in the United States, U. S. Department of Agriculture Farmers' Bulletin No. 1289.

(18) Storr-Best, Lloyd.
Varro on Farming, translation, London, 1912.

ADDITIONAL COPIES
OF THIS PUBLICATION MAY BE PROCURED FROM
THE SUPERINTENDENT OF DOCUMENTS
GOVERNMENT PRINTING OFFICE
WASHINGTON, D. C.
AT
15 CENTS PER COPY