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SECULAR AND SEASONAL CHANGES IN SOILS[1]

JOHN S. BURD[2] AND J. C. MARTIN[3]

(Contribution from the Laboratory of Plant Nutrition, University of California)

VARIATION IN YIELDS OF BARLEY AND IN NITROGEN CONTENT OF SOILS

In 1915 there was initiated in this laboratory a series of observations of the effects of cropping and fallowing upon the composition of a considerable number of soils (thirteen) assembled for that purpose. These observations have continued until the present and numerous studies of the data obtained have been made and published from time to time. A unique feature of this work has been the amount of attention paid to the liquid phase and the attempts which have been made to correlate crop production with concentration.

As invariably happens after a number of years in soil experiments where no fertilizers or amendments are used, the soils have attained a condition of relative equilibrium with respect to composition and, in the case of the plots under continuous crop, the yields also now vary but little from year to year.

When such a condition exists, further and prolonged periods must elapse or substantial changes in treatment must be inaugurated before

[1] It is recognized that the title of this paper would be entirely appropriate only in a monograph dealing with soils of all kinds. Unfortunately extensive studies of other soils involving the methods and point of view prevailing in this laboratory are not available for such a purpose. To conform to the restrictions required by a title of more limited scope would, in our view, unduly localize the implications fairly deducible from the work to be discussed hereinafter and particularly in the section on the liquid phase of the soils.

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sufficient additional evidence is obtained to warrant new generalizations as to soil behavior. Changes of treatment of entire plots cannot be made without detracting from the future use of the experiments for observing time effects, and the limited size of these plots precludes subdivision for the carrying out of critical experiments, without which conclusive explanations of the observed effects are not to be expected.

A natural period having been put to the further immediate acquisition of knowledge from this source,[5] it seems appropriate to present at this time a more comprehensive report of the work as a whole than has been necessary in the special studies heretofore published. In doing so, we propose to include a relatively complete record of the observations for the independent judgment of others, and to extend our previously expressed conclusions of the significance of the data with respect to the seasonal cycle and the progressive changes in soils to which nothing is added save pure water. These aims require the inclusion of some of the data published elsewhere, as well as the results of more recent observations during the past several years.

The details of the selection of the soils; history so far as known; physical classification and physical constants (moisture equivalents, hygroscopic coefficients, specific heats, mechanical analyses); the size, shape, arrangement, and construction of containers; methods of handling soils and laboratory methods of attack in use in the early years (1915 and 1916), are fully explained in a paper by Stewart.[6](11) In addition, complete chemical analyses (fusion), and analyses of hydrochloric acid, citric acid, and water extracts have been made and their significance discussed in an early paper.(1) Certain of the material hitherto published must be repeated here, but will be limited to that deemed essential to the unity of the present report and the convenience of readers.

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[5] For special experiments of a critical character not requiring large amounts of soil, it has been the practice to 'rob' the plots from time to time. This practice will doubtless be continued as occasion demands and thus prevent the entire elimination of the experimental material for current use.

[6] Special acknowledgment is due to Professor Stewart, in that, while these experiments were inaugurated at the suggestion of the present senior author and carried out under his authority, the details of arrangement and management upon which the success of enterprises of this kind so largely depend, were formulated and perfected by Professor Stewart, who directed the installations and the field and laboratory work from 1915 to 1919. His report of the first two years of the experiments contains the evidence which subsequent work has fully confirmed, of the indispensability of precise measurements of the liquid phase in interpreting the facts of soil behavior.

General Description of Arrangements

The thirteen soils described in table 1 were assembled at Berkeley in the spring of 1915, divided into three portions each, two for general studies and one for reserve and special experiments. The reserve

TABLE 1

Classification and History of the Soils Used in this Investigation*

<table>
<tr><th>Soil No.</th><th>Soil series and type</th><th>Origin</th><th>Crop grown</th><th>Previous history</th></tr>
<tr><td>1</td><td rowspan="5">Yolo silty clay loam</td><td>Sacramento Valley (Univ. Farm, Davis)</td><td>Field crops</td><td>Early planting of grain; 1909-1911, barley; 1912, fallow and manure; 1913-1914, barley.</td></tr>
<tr><td>2</td><td rowspan="2">Sacramento Valley (Yolo)</td><td>Almond orchard</td><td>Formerly grain; almond orchard 12 years old</td></tr>
<tr><td>3</td><td>Barley</td><td>Planted about 1860; since then barley and wheat, except sugar beets in 1911-1912.</td></tr>
<tr><td>4</td><td rowspan="2">Santa Clara Valley (San Jose)</td><td>Field crops</td><td>Originally grain; later orchard; several years alfalfa; three years field crops.</td></tr>
<tr><td>5</td><td>Prunes</td><td>Originally grain; prune orchard about 20 years old.</td></tr>
<tr><td>6</td><td>Yolo clay loam</td><td>Santa Clara Valley (Lawrence)</td><td>Peaches</td><td>Originally grain; peaches for 8 years; heavy crop, about 12 tons per acre.</td></tr>
<tr><td>7</td><td>Hanford fine sandy loam</td><td>Southern California (Arlington)</td><td>Oats</td><td>Originally grain; about 1890 put into alfalfa for 13 years; potatoes 2 years; alfalfa 4 years, oats 5 years; yield of oats, 4 tons of hay per acre.</td></tr>
<tr><td>8</td><td>Fresno fine sandy loam</td><td>San Joaquin Valley (Fresno)</td><td>Seedless grapes</td><td>Originally grain; 14 years in Sultanina (Thompson seedless) grapes. Production about 2 tons of raisins per acre for last 6 years.</td></tr>
<tr><td>9</td><td>Kimball fine sandy loam</td><td>Southern California (Redlands)</td><td>Navel oranges</td><td>25 years in oranges; previously bare land. A great variety of fertilizers had been used.</td></tr>
<tr><td>10</td><td>Tejunga fine sandy loam</td><td>Southern California (San Fernando Valley)</td><td>Peaches</td><td>Originally 15 years in prunes; now 10 years in peaches; small amount of manure the only treatment.</td></tr>
<tr><td>11</td><td>Madera fine sandy loam</td><td>San Joaquin Valley (Kearney Park)</td><td>Navel oranges</td><td>Orange trees about 15 years old.</td></tr>
<tr><td>12</td><td>Arnold fine sandy loam</td><td>San Joaquin Valley (foothills)</td><td>Oats</td><td>In cultivation about 40 years; early crops largely wheat; last 4 or 5 years biennial crops of oats; alternate year summer fallow.</td></tr>
<tr><td>14</td><td>Standish fine sandy loam</td><td>Honey Lake region</td><td>Virgin</td><td>Desert soil, small shrubs and weeds, natural growth.</td></tr>
</table>

* From: Stewart, G. R., Effect of season and crop growth in modifying the soil extract. in Jour. Agr. Res. **12** (*6*) 311-368, 1918

soil has been kept in closed wooden bins in the air-dry condition and drawn upon from time to time. In previous reports[4] these portions have been referred to variously as 'bin soils' or by the letter '*S*' together with the appropriate identification number.

The two portions of each soil used in the general experiments were placed in open galvanized iron containers, or tanks, 60 in. by 30 in. and 18 in. deep, suitably arranged for subirrigation[7] and insulated against lateral temperature changes by an external boxing filled with field soil. One tank of each soil has been continuously cropped to Beldi barley from 1915 to 1928, inclusive, and the soils so treated are known as '*A*' soils in the present and previous papers. The duplicate soils, known as '*B*' soils, were cropped to barley in 1915, lay fallow for ten years, and were again cropped to barley each year from 1926 to 1929, inclusive. No fertilizers or amendments have at any time been applied to either cropped or fallowed soils. The moisture requirements of both sets were met exclusively by the use of distilled water, the tanks being covered with water-tight canvas covers during rain storms and when precipitation was anticipated.

The original program of the experiments contemplated keeping the soils at a conventional optimum moisture content when actually under crop and adding water to fallowed soils, or to cropped soils between seasons, in proportion to the actual precipitation from time to time. This was found not to be feasible and a compromise method was adopted in the early years (1915–1919, inclusive), the optimum moisture content being maintained throughout the entire year in both cropped and uncropped soils. During this period the uncropped soils received a mechanical treatment equivalent to plowing and harrowing in the latter part of April of each year, at the same time that the cropped soils received a similar treatment preparatory to planting early in May. After 1919, no water was added between seasons to the cropped *A* soils and no water at all was permitted access to the *B* soils until the spring of 1926, when these were again brought to optimum moisture content and there maintained during the growing season (May to September) each year.

In previous papers the *B* soils (uncropped from 1916 to 1925, inclusive), have been referred to as 'fallowed.' Obviously the treatment just described is not equivalent to fallowing in the sense commonly used in field practice, but, as stated elsewhere, the term has been used as being more nearly descriptive of the treatment as a whole than that of any other abbreviated expression.

In considering certain phases of the discussion, particularly changes in nitrogen content, the differences of treatment in both sets of soils before and after 1919 must be kept in mind. Table 2 is supplied for ready reference on this point.

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[7] These tanks originally had a bottom outlet and overflow, but subdrainage was not permitted and the openings were later permanently closed.

TABLE 2

TREATMENT OF SOILS

<table>
<tr><th rowspan="2">Year</th><th colspan="2">Crop</th><th colspan="2">Mechanical treatment</th><th colspan="2">Water supply</th></tr>
<tr><th>A soils</th><th>B soils</th><th>A soils</th><th>B soils</th><th>A soils</th><th>B soils</th></tr>
<tr><td>1915</td><td>Barley</td><td>Barley</td><td>Mixed and screened (¼ in. mesh)</td><td>Mixed and screened (¼ in. mesh)</td><td colspan="2" rowspan="3">Continuously maintained (optimum) throughout the year</td></tr>
<tr><td>1916</td><td>Barley</td><td>None</td><td>Cultivated (9 in. depth)</td><td>Cultivated (9 in. depth)</td></tr>
<tr><td>1917-1919 inclusive</td><td>Barley</td><td>None</td><td>Cultivated (9 in. depth)</td><td>Cultivated (9 in. depth)</td></tr>
<tr><td>1920-1925 inclusive</td><td>Barley</td><td>None</td><td>Cultivated (9 in. depth)</td><td>None</td><td rowspan="2">Maintained during growing season only</td><td>Discontinued*</td></tr>
<tr><td>1926-1928 inclusive</td><td>Barley</td><td>Barley</td><td>Cultivated (9 in. depth)</td><td>Cultivated (9 in. depth)</td><td>Maintained during growing season only</td></tr>
<tr><td>1929</td><td>None</td><td>Barley</td><td>Cultivated (9 in. depth)</td><td>Cultivated (9 in. depth)</td><td>Discontinued</td><td>Maintained during growing season only</td></tr>
</table>

* Water content progressively decreased until surface soil contained hygroscopic moisture only.

In this table and in the text, as in previous papers, we have found it convenient to use the term 'optimum' in describing the condition of the soils with respect to moisture content. It is recognized that this term is frequently given a special meaning in physiological studies of moisture relations. Our use of the term is not, however, based upon any criterion involving precise measurements[8] but upon the response of the soil in terms of tilth. Having reached a decision as to what the moisture content of each soil should be, this was maintained as nearly as the conditions permitted, by adding water as appeared necessary from moisture determinations made from time to time. The conventional optima for the individual soils varied between 15 and 20 per cent for the silty clay loams and between 15 and 18 per cent for the sandy loams, all on the wet basis.

The original arrangement of the tanks with respect to each other is shown in figure 1, which applies to the period 1915 to 1919, inclusive. In 1920, circumstances beyond our control made it necessary to move[9] the installations to another location. This change afforded the opportunity for rearranging the tanks in such a way as to eliminate the shading effect of adjacent crops, the *A* tanks being alternated

[8] See Stewart(11) for moisture equivalents, etc.

[9] The tanks were moved without disturbing the soil.

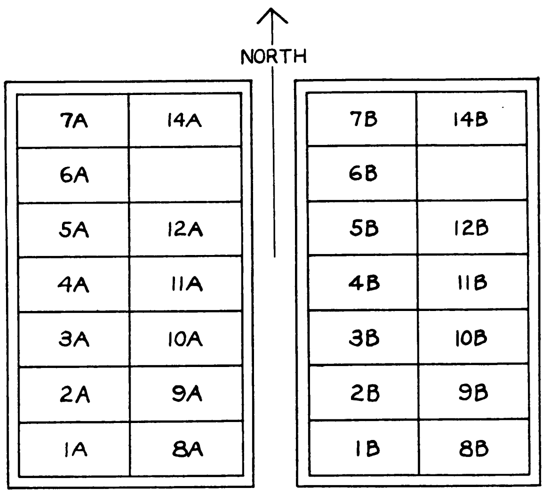

Fig. 1. Arrangement of soil containers, 1915–1919, inclusive.

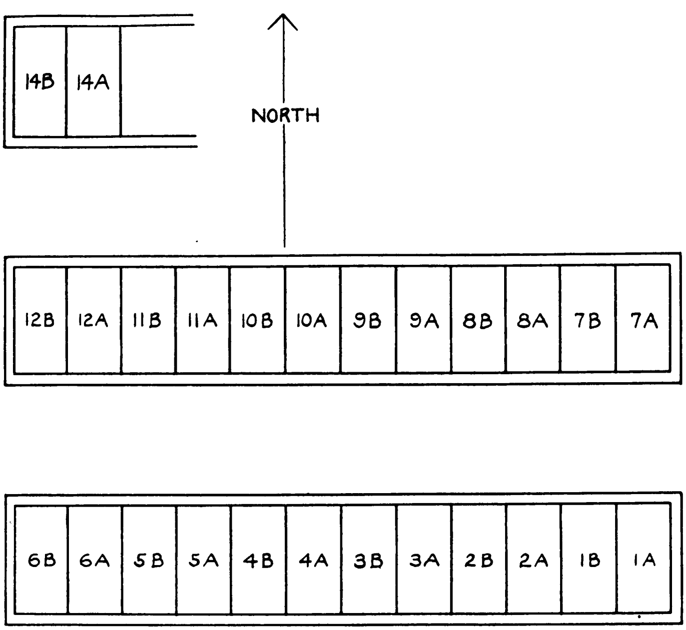

Fig. 2. Arrangement of soil containers, 1920–1925, inclusive

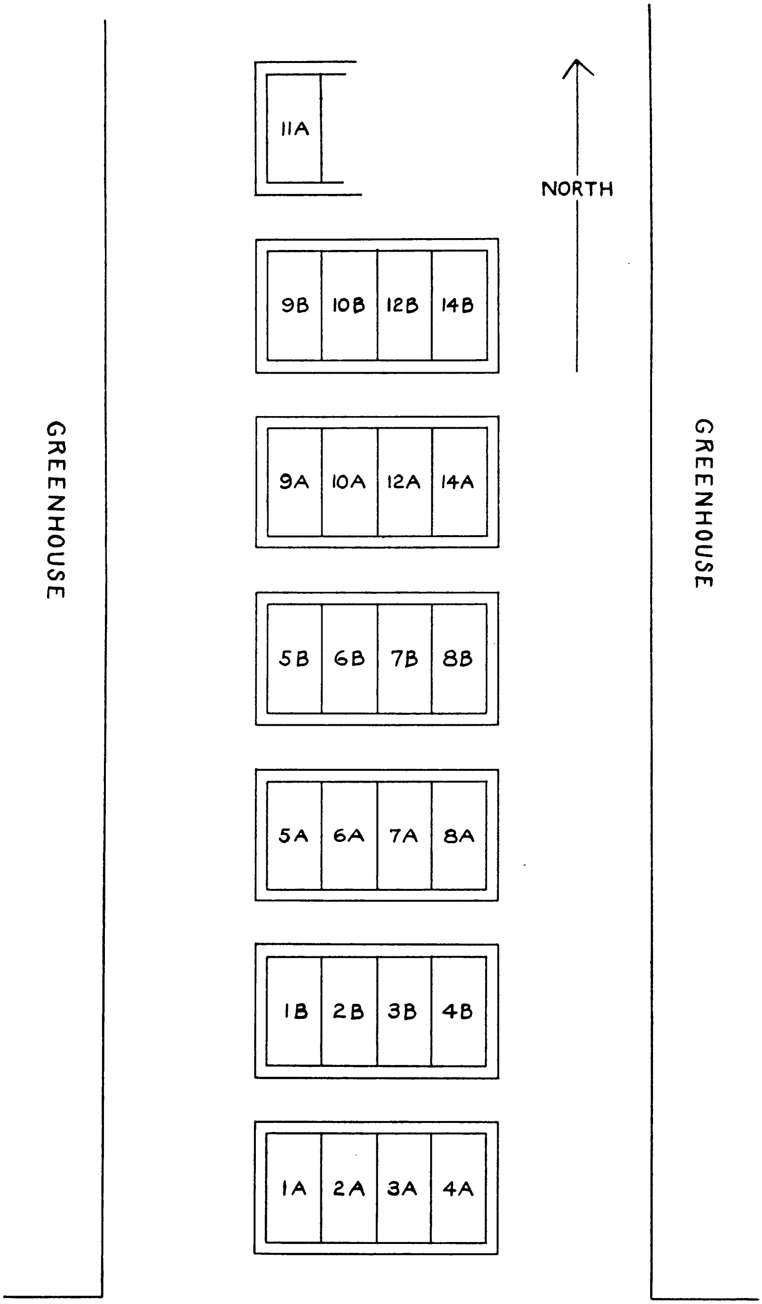

Fig. 3. Arrangement of soil containers from beginning of 1926.

with the *B* tanks (which bore no crops) as shown in figure 2. This arrangement continued throughout the period 1920–1925, inclusive, when it again became necessary to move the tanks. The arrangement of 1926, which still continues, is shown in figure 3. The purpose of the rearrangement at this time was to group the *A* soils together and the *B* soils together. This was deemed desirable as minimizing shading effects upon the crops from the *A* soils, of the larger crops anticipated and subsequently obtained from the *B* soils. Tank 11*B* is not shown in figure 3, because this soil was withdrawn drom the experiment and used for other purposes in 1921.

The location of the plots during the first and third periods was substantially the same and the different tanks were in the same horizontal plane. During the second period, however, they were located on the terraces of a south hillside, there being a three-foot difference in level between the successive rows of tanks shown in figure 2. The installation in this period was about 200 feet higher than, and about 600 yards distant from, that of the other locations.

Beginning with the season of 1920, the rate of planting was increased from 50 plants per tank, equivalent to 36 square inches per plant, to 105 plants per tank, equivalent to slightly less than 18 square inches per plant. The effect of various rates of planting (i.e., between 9 and 36 sq. in. per plant) upon yields of barley has been critically studied in this laboratory (unpublished manuscript). The results of that study showed that, in the range in question here, the total yields and draft upon the soils should be somewhat greater with the increased number of plants per unit area. The change in the procedure was introduced for the specific purpose of accentuating the latter effect. The increased rate of planting is not at all extreme, since barley is frequently given only 12 to 15 sq. in. per plant in field practice. The great falling-off in yields of the continuously cropped soils shown in the crop data, should be minimized, and hence made more significant, by the slightly more favorable conditions thus introduced in the later years. The method of sampling, involving the compositing of vertical cores from top to bottom of the tanks (18 in. deep) as described by Stewart[11] was continued throughout the entire series of years with one exception noted below, but the practice of replacing from the reserve supply the soil removed in sampling was discontinued in 1919.

Effect of Continuous Cropping on Yields

The complete record of yields from all of the continuously cropped *A* soils, is presented in table 3.[10] In considering these data, it must be kept constantly in mind that in such experiments variability of the soil is largely eliminated, cultivation and watering are uniform for each soil, losses due to birds, rodents, and insect pests are prevented and all of the conditions are made favorable to maximum production. It is not surprising, therefore, that some of these soils, of varied previous history (table 1), should in the first year of the experiment have given extremely large yields and that the relatively poor soils, under like conditions and at the same time, should have given crops which would be regarded as very acceptable under the conditions of field practice. For example, soil 8*A*, the best producer in 1915, gave a yield of 827 grams of grain, equivalent to 127 bushels per acre, and soil 12*A*, the poorest producer of that year, gave 242 grams, equivalent to 37 bushels per acre. The mean yield of all soils for the first three years was 547 grams of grain, equivalent to 84 bushels per acre, well above the economic minimum for the less favorable conditions of field practice. Such a result under the favorable conditions of the experiments at once suggests that the effects of cropping upon the producing power of the soil is not to be inferred from

[10] *Crop Records.* In harvesting the crops it has been the practice throughout the entire period of the experiments to pull the plants without detaching the root crown and adhering main roots. The original notes used by Stewart in his report of the first two years' work show that the "total yield of air-dry grain and straw" reported by him included parts of the roots in 1916, the weights of which are also a matter of record but were not published. From the method of harvesting known to have been used, and the extreme care in putting the data of 1915 and 1916 upon a comparable basis, it seems certain that the 1915 weights must have included the root crowns and adhering main roots, although it is nowhere so stated in the records. The present writers prefer to report their results in terms of the actual yields of air-dry grain and straw and to exclude the root crowns and adhering main roots, the weights of the latter being largely fortuitous, depending, on the one hand upon the completeness with which they are removed from the soil, and on the other, upon the extent to which the relatively heavy soil grains continue to adhere to the roots. The data reported herein for 1916, therefore, differ from those of Stewart for the same year by the weights of the root crowns and adhering main roots. Unfortunately, the actual weights of these portions of the crop of 1915 are not separately recorded but we may infer their magnitude from the data of subsequent years. The actual weights of the root material harvested in 1916 varied in the different plots between 60 and 121 grams with a mean of 81 grams; for 1917 the variation was between 55 and 114 grams with a mean of 93 grams. Since, as stated above, these variations are largely accidental and deviate from their means by amounts which are relatively small as compared with the total yields of crop, we feel justified in correcting the reported yields of the various plots in 1915 by deducting 81 grams, the mean weight of harvested roots for the succeeding year. The weights of grain are, of course, not affected by these corrections.

TABLE 3

YIELDS FROM TWO GROUPS OF SOILS* CONTINUOUSLY CROPPED TO BARLEY

Expressed as grams of air-dry material per container (12.5 sq. ft.)†

Group	Soil No.	1915	1916	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	Mean first 3 years 1915–1917	Mean last 3 years 1926–1928	Mean entire period 1915–1928
Total tops (grain, straw, and chaff)																		
Heavy soils	1A	2,011	1,376	1,319	710	820	721	758	582	566	650	416	409	808	433	1,569	550	827
	2A	1,957	1,409	1,114	592	1,057	815	398	561	448	584	405	563	564	508	1,460	545	784
	3A	1,340	897	765	539	921	733	654	400	489	552	412	543	673	463	1,001	560	670
	4A	1,250	1,192	1,124	860	1,003	665	739	422	583	592	412	650	719	569	1,189	646	770
	5A	1,782	1,582	1,423	1,130	1,269	771	1,057	662	681	723	644	1,001	1,081	807	1,596	963	1,044
	6A	2,206	1,434	1,069	520	821	712	641	437	477	417	374	459	507	550	1,570	505	758
	Mean	1,758	1,315	1,136	725	982	736	708	511	541	586	444	604	725	555	1,398	628	809
Light soils	7A	1,034	1,304	1,363	1,077	901	713	539	354	382	462	317	378	542	436	1,234	452	701
	8A	2,055	1,652	1,409	559	1,113	622	618	487	490	536	336	460	509	340	1,705	436	802
	9A	985	866	716	507	586	457	394	320	376	464	244	256	318	256	856	277	482
	10A	1,320	1,205	1,089	759	1,266	593	682	428	505	522	314	387	516	374	1,205	426	711
	11A	1,939	1,480	1,235	990	1,069	824	520	352	524	607	341	518	499	553	1,551	523	819
	12A	715	894	824	655	641	513	534	317	330	502	264	345	379	280	811	335	513
	14A	1,283	1,383	1,051	955	986	507	709	470	508	557	302	347	449	271	1,239	356	698
	Mean	1,333	1,255	1,098	793	937	604	572	390	445	521	302	384	459	359	1,229	401	675
Grain																		
Heavy soils	1A	730	675	624	315	324	374	375	287	256	309	192	160	415	208	676	261	374
	2A	605	655	544	240	494	440	186	271	190	265	169	257	260	244	601	254	344
	3A	474	439	358	223	443	385	314	188	208	259	183	235	334	223	424	264	305
	4A	534	549	511	344	473	359	360	197	257	275	178	295	345	265	531	302	353
	5A	529	690	663	461	616	408	509	313	309	336	298	475	543	395	627	471	467
	6A	739	670	540	217	421	362	296	219	196	169	158	202	249	271	650	241	336
	Mean	602	613	540	300	462	388	340	246	236	269	196	271	358	268	585	299	364
Light soils	7A	432	541	660	455	423	376	270	167	177	205	133	166	282	219	544	222	322
	8A	827	679	630	250	520	310	324	205	208	220	148	208	257	174	712	213	354
	9A	388	357	331	224	234	231	197	141	151	210	106	114	163	126	359	134	212
	10A	495	551	482	275	633	320	324	196	194	231	131	171	246	184	509	200	319
	11A	742	625	545	402	499	429	257	153	222	256	140	242	209	274	637	242	357
	12A	242	390	360	269	280	264	249	143	134	205	106	144	176	132	331	151	221
	14A	390	630	507	453	454	254	346	220	225	260	126	149	190	105	509	148	308
	Mean	502	539	502	333	435	312	281	175	187	227	127	171	218	173	514	187	299

* For special description and previous history of soils see table 1. † To convert grams per container to pounds per acre, multiply by $\left(\frac{43,560}{2.5\times5.0\times453.6}\right)$ or by 7.68.

the absolute yields per unit area, but from the relative yields from time to time.

Inspection of table 3 shows that the mean yield of vegetative material during the first three years was 1,398 grams per container for the heavy and 1,229 grams for the light soils, and declined to 628 grams (45 per cent) and to 401 grams (33 per cent), respectively, in the last three-year period. Do these declines represent a relative loss of producing capacity inseparably connected with continuous cropping to barley for a comparatively short period (14 years) or were they caused or accentuated by the special conditions of the experiment? The special conditions which may have affected the results are as follows:

1. Just before the first crop all soils were collected, partially air-dried and sifted through a ¼-in. screen—a treatment much more intensive than the ordinary mechanical field operations.

2. From 1915 to 1919, inclusive, the soils were kept moist between seasons and while the crop was growing.

3. The location of the plots from 1920 to 1925, inclusive, was different and probably less favorable to vegetative production than during the preceding or following period.

It is a matter of common experience that intensive cultivation is especially favorable to the immediate productivity of the heavier types of soil and may be either favorable or unfavorable to lighter types. The data show that all of the heavy soils produced larger crops in 1915 than in any subsequent period and that their superiority in that year was, for the most part, very substantial. Similar differences may be observed for two of the lighter soils (8*A*, 11*A*); two others gave only slightly superior yields in 1915 (9*A*, 10*A*); while three (7*A*, 12*A*, 14*A*) gave lower yields in 1915 than in 1916. These results suggest that the first year's yields of the heavy soils were probably abnormally high due to the initial intensive mechanical treatment. Moreover the relatively large yields of several of the more productive soils of this group in 1916 and 1917, as compared with subsequent yields, may also have been due to a continuation of the favorable conditions resulting from the same cause.

The differences in behavior of the individual soils in the light group, while quite consistent with the known effects of mechanical treatment of such soils, leaves doubt as to whether or not the crops on these soils in the early years are to be regarded as abnormally high. The abruptness of their decline in yield subsequent to 1917 suggests, however, that the yields in the early years, of the group as a whole, may be abnormally high owing to the special treatment noted. On the other hand, the substantial declines in mean yields of both groups subsequent to 1917 may be associated with the second of the special conditions enumerated above, namely, the continued maintenance of optimum moisture content throughout the year in all soils up to 1919. As will be shown later, there was a decrease of substantial magnitude in the total nitrogen content in this period. That these losses of nitrogen were due to the treatment, is shown by the fact that the observed losses occurred in the continuously fallowed (duplicate) soils as well as in those which were continuously cropped.

The third of the special conditions noted, namely, that the location of the soils in the period 1920–1925, inclusive, was a different and probably a less favorable one than during the preceding or following periods, remains to be considered. This location was on a south hillside at the mouth of a canyon where air movements and meteorological conditions are certainly different than those of the gently sloping open space of the other locations. Moreover actual measurements showed that the mean length of day during the growing season was between one and two hours shorter than that of the other locations. It seems a reasonable inference, therefore, that the yields during this period were probably somewhat inferior to those which would have been obtained had the plots remained in their original location.

Our conclusion is that the yields in the early years of the experiment are probably somewhat higher than they would have been had they remained in place in the field and received the same attention and protection as that afforded by the experimental conditions; that the abruptness of the decline after 1917, while accentuated by the losses of total nitrogen known to have occurred between 1915 and 1919, was caused in part by the intervention of a very poor growing season in 1918, and by abnormally low yields in the subsequent period, 1920–1925, due to the rather less favorable growing conditions in the location of the plots during that period; that the declines in yield of the two groups of soils as measured by the mean yields for the first and last three-year periods, are possibly somewhat extreme as measures of the potential ability of the soils to produce vegetative material, but do represent the order of magnitude of the loss of producing capacity.

The various differences in behavior and crop yields of the two groups of soils, as brought out before, and other differences (see total nitrogen contents, table 6) to be discussed later, clearly require some attempt to correlate crop production with soil texture. With the possible exception of soil 6 of the heavy group, we feel that the division into groups is warranted by the differences in physical properties (see Stewart[(11)]) shown by the mechanical analyses and by those intangible qualities (tilth) observed throughout the fourteen seasons they have been under cultivation.

Figure 5 presents a graphic comparison between the crop yields of the most productive[11] (8*A*) and of the least productive (12*A*) of the light soils, with the means of the groups of heavy and light soils.[12] A similar graph, figure 4, compares the best and poorest of the heavy soils with the mean yields of the two groups. Referring to the figures, it is seen that the mean yields of the heavy soils have been continuously greater than those of the light soils every year save 1918, which gave definitely abnormal yields for each soil. The very productive light soil (8*A*) gave superior yields to those of the heavy soils during the early years (see also 11*A*, table 3) but subsequently has fallen below the latter as a group. The originally unproductive light soil 12*A* has continuously maintained its inferior position with respect to both heavy and light groups. The most productive heavy soil (5*A*) has been a superior producer throughout. The originally least productive heavy soil (3*A*) remained relatively unproductive for some years, but is now definitely superior to the light soils as a group.

A summary based on relative production shows that the six most productive soils in total weight of crop and in grain during the first three years included four heavy and two light soils. The soils were Nos. 8, 5, 6, 1, 11, and 2 in order of weight of total crop, and 8, 1, 6, 11, 5, and 2 in order of weight of grain. Some of the differences upon which this order is based are small and are not significant as between soils within a group. A similar summary for the last three years shows that the six most productive soils at present include five heavy and one light soil. These are 5, 4, 3, 1, 2, and 11, in order of weight of total crop and of grain. Moreover, the least productive of all of the heavy soils (6*A*) is not significantly inferior to the best of the light group. While some of the differences may not be significant, the tendency for the lighter soils to fall and for the heavy soils to rise in the scale of relative production is evident.

The relatively inferior clay loam 6*A*, a soil which has always been difficult to handle and which becomes more so from year to year because of unfavorable physical properties, is the most colloidal of all

[11] The criterion of productiveness here used is the mean yield of total crop weight during the first three years.

[12] The individual data for the other soils is omitted from the graphs in order to avoid confusion of lines (see table 3 for other data).

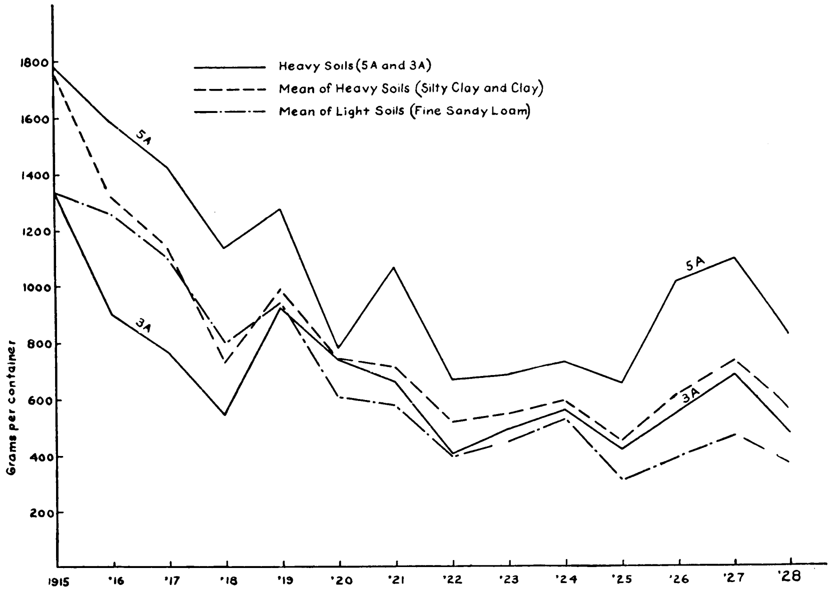

Fig. 4. Yields (barley) of the most productive and least productive heavy-textured soils and mean yields of groups of heavy and light soils.

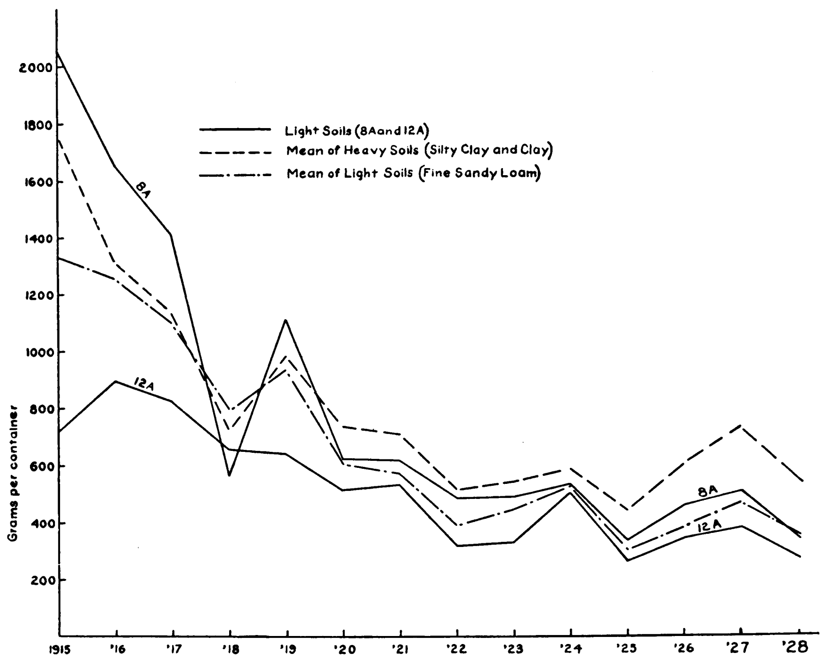

Fig. 5. Yields (barley) of the most productive and least productive light-textured soils and mean yields of groups of heavy and light soils.

of our soils, and the same one which gave a very large yield in 1915, apparently the result of response to the unusually intensive mechanical treatment of that year. Under the subsequent more nearly normal treatment, particularly when attended by the deflocculating effect incidental to declining concentrations in the liquid phase, the behavior observed is not difficult to explain.[7] It can hardly be doubted that the absolute declines in production of the other heavy soils is, in part, due to the last-mentioned effect. Soil 6 is merely more susceptible in this respect.

The point which we wish to emphasize here is, not that heavy soils are necessarily more productive than lighter types, nor that they inevitably decline less rapidly in producing power, but merely that in general they tend to maintain their rate of production on a higher plane unless prevented by the development of some adverse condition. The limiting condition most to be apprehended would appear to be the unfavorable tilth resulting from the deflocculation of such soils as a result of lowered concentrations in the liquid phase brought about by cropping.[7] Soils which by any reasonable standard can be classified as 'light' do not suffer from this disability and their decline in productivity is doubtless referable to unfavorable chemical or biological changes. The superiority of heavy soils which do not develop a markedly unfavorable physical condition is, of course, not due to 'heaviness' or colloidality as such, but to the greater supplying power incident to the possession of these properties.

Effect of Continuous Fallowing on Yields

In the preceding discussion of the effects of continuous cropping, the mean yields for the first and last three-year periods have been used as the basis for comparison. For the present comparison, data for the initial period are limited to one year (1915). As stated previously, the 1915 data are subject to the objection that the very vigorous mechanical treatment and drying out of the soils incident to sifting and mixing immediately before planting, represents an abnormal condition in that year which was, in general, favorable to a greater production of total dry matter in the heavy soils. The effects of abnormal yields the first year upon our conclusions as to the magnitude of the decline in crop-producing capacity of the continuously cropped soils, were doubtless minimized by the averaging of the first three years, during which period the effects of the unusual treatment of the soils in 1915 had had an opportunity to wear off. A similar method is not practicable in the present comparison because the period of fallowing began in the second year of the experiments.

That the yields of 1915 are to be regarded as abnormal is further indicated by the difference in ratio of grain to straw as compared with those of all other years, as will be seen in table 4. The fact that the mean ratio (81 per cent) for the *A* soils in 1916, when these were in a 'high' state of fertility, is very close to the ratio for the last three years (89 per cent), when yields had fallen to less than half, justifies the opinion that something other than the condition of the soil is the cause of the wide variation which characterized the ratio (56 per cent) of 1915. The most obvious cause is to be found in the

TABLE 4

RATIOS OF GRAIN TO STRAW AND CHAFF

Means of all soils expressed as percentages.

Year	*A* soils	*B* soils	Year	*A* soils	*B* soils
1915	56	56	1922	87	....
1916	81	....	1923	75	....
1917	87	....	1924	81	....
1918	72	....	1925	76	....
1919	87	....	1926	81	82
1920	109	....	1927	94	97
1921	94	....	1928	93	86

later dates of planting and harvesting (a month to six weeks) in that year. Whatever the cause of this extreme variation, it is evident that the 1915 data must be used with caution and it would seem that a fairer basis for the present comparisons is afforded by the data from the *A* soils in 1916 and 1917. Surely the yields of the *B* soils, had they been planted in those years, should have been substantially the same as those of the *A* soils for the same period since the two sets had had an identical history and treatment. The only possible objection to the use of the *A* data as representing the original crop-producing power of the *B* soils in comparison with the data of recent years would appear to be that the later yields might have been substantially affected had the *B* soils actually been cropped in 1916 and 1917. This possibility seems remote on *a priori* grounds and the very striking differences brought out in our studies of nitrogen fluctuations testify to the relative importance of soil management and treatment as compared with the influence of the crop and suggests that the 1926 and subsequent yields of the *B* soils could hardly have been seriously affected had several additional crops been grown in the early years of the experiments.

The period subsequent to fallowing of the *B* soils is represented by the crops of 1926, 1927, 1928, and 1929. It is evident that the effect of fallowing upon yield could best be measured on a basis of the 1926 yields were it not for the factor of seasonal variation and that the latter can only be minimized by including a series of subsequent crops. The season of 1928 was definitely unfavorable to crop production, as is clearly shown by the decline in yields of the continuously cropped soils (table 3) between 1927 and 1928. In table 5, therefore, the data for each of the years in question has been included, but the mean yields of the *A* soils in 1916–1917 and those of the *B* soils in 1926–1927 have been used as the basis for comparison.

Inasmuch as it is impossible to state with any confidence the degree of significance to be attached to the percentage changes in yield, it is obvious that improvement in the condition of a given soil may only be inferred when the change is relatively large. In making comparisons, it may be noted at once that where the percentage changes are at all substantial, the increases in yields of total dry matter and of grain are very similar for each soil with the exception of soils 9 and 12. The increases of dry matter and of grain were respectively 28 per cent and 51 per cent for soil 9, and 48 per cent and 60 per cent for soil 12. In both of these cases, however, the increase in dry matter is sufficiently great to warrant the opinion that there has been a substantial gain in producing capacity of the soils in question even in the absence of the confirmatory evidence afforded by the still larger yields of grain.

Comparing the records of the various soils within each group, it appears that soils 3 and 4 of the heavy group and soils 9, 10, and 12 of the light group have responded very markedly to the fallowing treatment. The large percentage increase in yield of soil 4 is obviously due to the extraordinarily large crop of 1927 included in the mean for the period subsequent to fallowing and which we are entirely unable to explain. The yields of soil 3, however, show no such differences between the seasons 1926 and 1927, the figures for yields of total dry matter conforming very well with the degree of superiority shown in 1927 by the continuously cropped soils (compare yields in 1926 and 1927, table 3).

Of the three light soils showing a response to the fallowing treatment, soils 9 and 12 gave larger yields in 1926 than they did in the more advantageous season of 1927, while soil 10 gave an enhanced yield in the latter season and did not begin to show a reduction in yield until the less favorable season of 1928 (see table 3).

TABLE 5

INITIAL YIELDS* OF CONTINUOUSLY CROPPED SOILS (A) AND SUBSEQUENT YIELDS OF FALLOWED SOILS (B)

Expressed as grams of air-dry material per container (12.5 sq. ft.)

Group	Soil No.	*A* soils			*B* soils				Mean of *A* soils 1916–1917	Mean of *B* soils 1926–1927	Gain (+) or loss(−), per cent
		1915	1916	1917	1926	1927	1928	1929			
					Total tops (grain, straw, and chaff)						
Heavy soils	1	2,011	1,376	1,319	1,345	1,386	1,046	600	1,348	1,366	+ 1
	2	1,957	1,409	1,114	1,191	1,768	823	497	1,262	1,480	+17
	3	1.340	897	765	1,416	1,583	509	441	831	1,500	+81
	4	1,250	1,192	1,124	1,363	2,268	1,196	518	1,158	1,816	+57
	5	1,782	1,582	1,423	1,563	2,136	1,497	796	1,503	1,850	+23
	6	2,206	1,434	1,069	1,410	1,532	549	378	1,252	1,471	+18
	Mean	1,758	1,315	1,136	1,381	1,779	933	538	1,226	1,580	+29
Light soils	7	1,034	1,304	1,363	1,105	1,588	605	432	1,334	1,347	+ 1
	8	2,055	1,652	1,409	1,434	1,562	616	508	1,531	1,493	− 3
	9	985	866	716	1,094	924	378	363	791	1,009	+28
	10	1,320	1,205	1,089	1,364	1,703	432	442	1,147	1,534	+34
	12	715	894	824	1,370	1,175	409	295	859	1,273	+48
	14	1,283	1,383	1,051	1,348	1,347	489	346	1,217	1,348	+11
	Mean	1,232	1,217	1,075	1,286	1,383	488	398	1,146	1,335	+16
					Grain						
Heavy soils	1	730	675	624	579	691	512	311	650	635	− 2
	2	605	655	544	548	868	368	238	600	708	+18
	3	474	439	358	670	795	225	214	399	733	+84
	4	534	549	511	582	1,068	583	248	530	825	+56
	5	529	690	663	662	993	704	399	677	828	+22
	6	739	670	540	623	759	258	175	605	691	+14
	Mean	602	613	540	611	862	442	264	577	735	+27
Light soils	7	432	541	660	501	801	273	207	601	651	+ 8
	8	827	679	630	600	766	283	240	655	683	+ 4
	9	388	357	331	551	484	170	166	344	518	+51
	10	495	551	482	598	878	192	215	517	738	+43
	12	242	390	360	620	575	167	138	375	598	+60
	14	390	630	507	667	642	207	162	569	655	+15
	Mean	462	525	495	590	691	215	188	510	641	+26

* For subsequent yields of *A* soils, see table 3.

Considering the three soils showing a general consistency of behavior, both in the continuously cropped and fallowed series, i.e., soils 3, 9, and 12, it is to be noted that these are the ones which in 1916 and 1917 gave the low yields in each of their respective groups (table 5) and they are the same ones which under continuous cropping (table 3) gave markedly lower mean yields, both of vegetative matter and of grain, than any other soil in their respective groups for the entire period of fourteen years. These facts tend to confirm the general belief that it is the so-called 'poor soils' which respond to fallowing in the greatest degree. It is evident, however, that the criteria of 'goodness' or 'poorness' in soils require more exact definition than that implied by experience in obtaining large or small crops. Soils in which the causes of infertility are obscure, or if recognizable, are capable of remedy by simple methods, must be differentiated from soils infertile because of basic deficiencies, generally recognizable as such and which can only be corrected by large applications of fertilizers or by green manuring or by frequent fallowing.

The relatively large increase in yield of soils 3, 9, and 12 the first year after fallowing (1926) is associated with a large accumulation of nitrates (table 6). As shown by Stewart[11] the nitrate content of all three of these soils was low in 1915 and 1916, and subsequent experience has confirmed the view that their supplying power for nitrates is exceedingly low if crops are grown each year. The nitrate expressed as nitrogen was 0.001 per cent (table 6) or less in these soils in 1915 but had risen after the prolonged fallowing (1926) to 0.010 per cent in the case of soil 3 and to 0.004 per cent and 0.006 per cent in soils 9 and 12, respectively. There can be but little doubt that these enormous accumulations of nitrate nitrogen must have been an important factor in determining the great increase in crop yield from these three soils in 1926.

The real difference between soil 3 on the one hand, and soils 9 and 12 on the other, is shown by the fact that the former maintained its production the second year after the cessation of the fallowing, while the latter gave lower yields both of total vegetative matter and of grain in 1927, in spite of the fact that the climatic factor, as previously noted, was much more favorable in that year. Moreover, a seasonal study of nitrate fluctuations in all of the previously fallowed soils in the cropping season of 1926 (table 12) showed declines from the high levels caused by fallowing, and the nitrate levels of soils 9 and 12 were greatly inferior to that of soil 3 at the time of harvesting the crops. The maintenance of the yield of soil 3 and the decline in yields of soils 9 and 12 may perhaps be associated with this difference. However this may be, it seems clear that the rehabilitation of soils 9 and 12 is of an ephemeral character and yields may be expected to decline as the accumulation of solutes (particularly nitrate) is reduced to the normal and relatively low equilibrium concentrations which appear to characterize such soils under the conditions of continuous cropping.

In a previous paper[4] fallowing was shown to have brought about a slight decline in concentration of the liquid phase of soil 8. The subsequent observation of an apparent decline in production of that soil is consistent with this. Apart from a consideration of the chemical data to be discussed later, the differences shown appear to indicate either that some of the soils were initially in a condition of maximum fertility (for each soil) or were made so by the vigorous mechanical treatment of 1915, so that in spite of the length of the fallowing, they have been unable to give any further response in terms of increased yields. Soils 3, 9, and 12 are, obviously, not in that category and have responded to the prolonged fallowing. It is, perhaps, unnecessary to point out that a much shorter period of fallowing might have produced the same result.

Nitrogen Fluctuations in Cropped and Fallowed Soils

One of the peculiar merits of long-time experiments with soils is the tendency to eliminate from the conclusions the effects of experimental errors of sampling and analysis. This applies particularly to nitrogen fluctuations because this element is subject to highly localized accretions from natural causes (nitrogen fixation) and because losses also may be localized as a result of effects upon the biological complex of variations in moisture, aeration, etc., within a given soil mass, which can neither be entirely eliminated nor controlled. In annual experiments, the sampling error may equal or exceed the magnitude of the variation.

Obviously no rule can be laid down as to the minimum time experiments should continue in order to produce changes of nitrogen content which may be legitimately regarded as significant. Certainty in this regard can only be attained as a result of the rational interpretation of statistical data obtained from large numbers of individual determinations from each soil. Such data are obviously not obtainable from small plots without unduly exhausting the supply of soil and the reader must judge of the significance of the present results from the intrinsic evidence of the general trends and magnitudes of the observed variations.

The completed data are presented in table 6. The sampling of the soils with the exception of 1926 was by compositing ten equally distributed vertical cores from each tank (12½ sq. ft.) to the entire depth of the soil (18 in.). In columns 2 and 11 are shown the total nitrogen contents of all soils at the beginning of the first season. The most extreme variation between the two sets for any soil is 0.004 per cent between the *A* (0.095 per cent) and *B* (0.099 per cent) tanks of soil 10. This same soil when continuously cropped until 1919 showed a loss of 0.031 per cent nitrogen and when continuously fallowed for a corresponding period a loss of 0.029 per cent nitrogen. Like comparisons for the other soils show, similarly, a large spread between the differences of duplicate composites in 1915 and the apparent losses due to cropping and fallowing in all cases except soil 11 under fallowing. Such a result appears to establish the significance of the various observed changes and to validate the procedure used in sampling.

In 1926, it seemed desirable to take separate samples to ascertain something of the variations within given masses of soil originally homogeneous but which had been in place for some (eleven) years. The samples were accordingly drawn in single cores taken from the center of the north and south half of each tank, respectively, and divided into two equal portions representing the upper (surface) 9 in. and the lower 9 in. layers. The mean of these four samples from each tank is taken to represent the composition of the soil as a whole. This change necessitates a brief consideration of the propriety of using a mean derived from such a limited number of samples.

If the data of column 4 are compared with the means of the corresponding four determinations of column 7, it will be observed that there is an apparent increase of nitrogen in all cropped soils during the period in question with the exception of soil 8, which shows an apparent decrease. In all cases where increases appear in the cropped soil as inferred from the mean of column 7, the conclusion would be the same if the lowest determination of the 1926 samples had been used as the basis of comparison, with the exception of soils 6 and 7, where in each case, one determination from the subsoil in 1926 showed a lower figure than the composite for 1919. The other three determinations are, however, consistently higher and the preponderance of evidence would appear to justify the use of the mean.

Similar comparisons for the fallowed soils (compare cols. 13 and 16, table 6) also show in the majority of cases that all four of the individual samples of 1926 apparently contained more total nitrogen than that indicated by the corresponding composite for 1919. Several exceptions occur, however, notably in soil 4, where an apparent increase of total nitrogen rests upon a single determination representing a large deviation from the mean and vitiating this value as a basis of comparison. Soils 7, 8, and 14 each show one or two determinations out of the four made in 1926 which equal or fall below those of the

TABLE 6

Total Nitrogen in Cropped Soils*

Expressed as percentage of nitrogen (N) in water-free soil.

Continuously cropped soils

Soil No.	June 1915	June 1918	Nov. 1919	Feb. 1923	Dec. 1924	January 1926		Nov. 1927
	Straight Kjeldahl + NO_3 as N	Straight Kjeldahl + NO_3 as N	Straight Kjeldahl + NO_3 as N	Straight Kjeldahl + NO_3 as N	Straight Kjeldahl + NO_3 as N	Modified Kjeldahl to include NO_3 as N	Nitrate (NO_3) as N	Modified Kjeldahl to include NO_3 as N
1	*2*	*3*	*4*	*5*	*6*	*7*†	*8*†	*9*
						.114	*.000*‡	
1*A*	.147	.121	.105	.112	.106	.125	*.001*	.112
						.112	*.000*	
	.002‡	*.002*	*.001*	*.000*	*.001*	.117	*.001*	*.000*
						Mean, .117	Mean, *.001*	
						.122	*.001*	
						.126	*.001*	
2*A*	.137	.120	.101	.108	.107	.122	*.001*	.109
						.113	*.001*	
	.001	*.002*	*.001*	*.001*	*.001*	Mean, .120	Mean, *.001*	*.000*
						.172	*.001*	
						.158	*.001*	
3*A*	.180	.144	.144	.168	.152	.162	*.001*	.150
						.168	*.000*	
	.001	*.002*	*.001*	*.016*	*.001*	Mean, .165	Mean, *.001*	*.000*
						.112	*.000*	
						.114	*.001*	
4*A*	.129	.117	.107	.117	.106	.112	*.000*	.109
						.113	*.001*	
	.001	*.002*	*.001*	*.013*	*.001*	Mean, .113	Mean, *.001*	*.000*
						.122	*.000*	
						.122	*.000*	
5*A*	.145	.134	.118	.124	.118	.123	*.000*	.117
						.128	*.000*	
	.001	*.002*	*.001*	*.008*	*.001*	Mean, .124	Mean, *.000*	*.000*
						.121	*.001*	
6*A*	.143	.115	.110	.120	.103	.118	*.000*	.118
						.119	*.001*	
	.001	*.002*	*.001*	*.013*	*.001*	.108	*.000*	*.001*
						Mean, .116	Mean, *.001*	
						.060	*.001*	
						.057	*.001*	
7*A*	.075	.065	.053	.054	.050	.052	*.000*	.052
						.055	*.000*	
	.000	*.001*	*.001*	*.000*	*.001*	Mean, .056	Mean, *.001*	*.000*

* Data are from composite samples from entire container, except in columns 7, 8, 16, and 17.

† Four samples were taken and separately analyzed in 1926; in this table the first sample listed for each soil is from the upper north center of the tank, the second from the upper south center, the third from the lower north center, and the fourth from the lower south center.

‡ All figures in italics are nitrate (NO_3) expressed as percentages of nitrogen (N) in the water-free soil.

TABLE 6 (*Continued*)

Continuously cropped soils

Soil No.	June 1915	June 1918	Nov. 1919	Feb. 1923	Dec. 1924	January 1926		Nov. 1927
	Straight Kjeldahl + NO_3 as N	Straight Kjeldahl + NO_3 as N	Straight Kjeldahl + NO_3 as N	Straight Kjeldahl + NO_3 as N	Straight Kjeldahl + NO_3 as N	Modified Kjeldahl to include NO_3 as N	Nitrate (NO_3) as N	Modified Kjeldahl to include NO_3 as N
1	*2*	*3*	*4*	*5*	*6*	*7*†	*8*†	*9*
						.044	*.000*‡	
8*A*	.075	.053	.046	.046	.042	.044	*.001*	.038
						.042	*.000*	
	.002	*.001*	*.001*	*.001*	*.001*	.042	*.000*	*.000*
						Mean, .043	Mean, *.000*	
						.044	*.000*	
						.045	*.000*	
9*A*	.051	.043	.039	.047	.035	.047	*.000*	.036
						.042	*.000*	
	.000	*.001*	*.001*	*.010*	*.001*	Mean, .044	Mean, *.000*	*.000*
						.075	*.001*	
						.073	*.001*	
10*A*	.095	.073	.064	.077	.065	.069	*.000*	.063
						.073	*.001*	
	.002	*.002*	*.001*	*.010*	*.001*	Mean, .072	Mean, *.001*	*.000*
						.057	*.000*	
11*A*	.077	.062	.052	.059	.052	.062	*.001*	.052
						.058	*.001*	
	.002	*.001*	*.001*	*.007*	*.001*	.060	*.001*	*.000*
						Mean, .059	Mean, *.001*	
						.048	*.001*	
						.048	*.000*	
12*A*	.055	.047	.038	.046	.038	.046	*.000*	.038
						.046	*.000*	
	.001	*.001*	*.001*	*.006*	*.000*	Mean, .047	Mean, *.000*	*.000*
						.060	*.000*	
						.059	*.000*	
14*A*	.071	.061	.049	.065	.050	.060	*.000*	.051
						.059	*.000*	
	.001	*.001*	*.000*	*.011*	*.001*	Mean, .060	Mean, *.000*	*.000*

* Data are from composite samples from entire container, except in columns 7, 8, 16, and 17.

† Four samples were taken and separately analyzed in 1926; in this table the first sample listed for each soil is from the upper north center of the tank, the second from the upper south center, the third from the lower north center, and the fourth from the lower south center.

‡ All figures in italics are nitrate (NO_3) expressed as percentages of nitrogen (N) in the water-free soil.

TABLE 6 (*Continued*)

TOTAL NITROGEN IN FALLOWED SOILS*

Soils fallowed ten consecutive years, 1916-1925 inclusive; cropped, 1926 1927 inclusive

Soil No.	June 1915	June 1918	Nov. 1919	Feb. 1923	Dec. 1924	January 1926		Nov. 1927
	Straight Kjeldahl + NO_3 as N	Straight Kjeldahl + NO_3 as N	Straight Kjeldahl + NO_3 as N	Straight Kjeldahl + NO_3 as N	Straight Kjeldahl + NO_3 as N	Modified Kjeldahl to include NO_3 as N	Nitrate (NO_3) as N	Modified Kjeldahl to include NO_3 as N
10	*11*	*12*	*13*	*14*	*15*	*16*†	*17*†	*18*
						.162	*.048*‡	
1*B*	.145	.127	.118	.130	.145	.154	*.039*	.117
						.123	*.013*	
	.002	*.006*	*.009*	*.016*	*.017*	.127	*.006*	*.003*
						Mean, .141	Mean, *.024*	
						.151	*.041*	
2*B*	.138	.120	.116	.143	.157	.121	*.021*	.110
						.125	*.006*	
	.001	*.004*	*.005*	*.020*	*.022*	.122	*.008*	*.001*
						Mean, .130	Mean, *.019*	
						.168	*.015*	
3*B*	.178	.147	.151	.183	.177	.171	*.018*	.156
						.159	*.003*	
	.001	*.004*	*.005*	*.024*	*.013*	.174	*.004*	*.001*
						Mean, .168	Mean, *.010*	
						.105	*.004*	
4*B*	.128	.121	.117	.175	.162	.141	*.033*	.104
						.113	*.008*	
	.001	*.005*	*.008*	*.040*	*.033*	.112	*.005*	*.002*
						Mean, .118	Mean, *.012*	
						.155	*.028*	
5*B*	.145	.137	.131	.175	.128	.160	*.028*	.120
						.135	*.002*	
	.001	*.005*	*.007*	*.031*	*.025*	.138	*.004*	*.003*
						Mean, .147	Mean, *.016*	
						.144	*.017*	
6*B*	.142	.115	.114	.137	.138	.142	*.017*	.116
						.133	*.006*	
	.001	*.004*	*.010*	*.020*	*.014*	.140	*.007*	*.001*
						Mean, .140	Mean, *.012*	
						.061	*.001*	
						.067	*.007*	
7*B*	.072	.065	.063	.074	.090	.065	*.003*	.054
						.066	*.006*	
	.001	*.002*	*.006*	*.015*	*.021*	Mean, .065	Mean, *.004*	*.000*

* Data are from composite samples from entire container, except in columns 7, 8, 16, and 17.

† Four samples were taken and separately analyzed in 1926; in this table the first sample listed for each soil is from the upper north center of the tank, the second from the upper south center, the third from the lower north center, and the fourth from the lower south center.

‡ All figures in italics are nitrate (NO_3) expressed as percentages of nitrogen (N) in the water-free soil.

TABLE 6 (*Concluded*)

Soils fallowed ten consecutive years, 1916-1925 inclusive; cropped 1926-1927 inclusive

Soil No.	June 1915	June 1918	Nov. 1919	Feb. 1923	Dec. 1924	January 1926		Nov. 1927
	Straight Kjeldahl + NO_3 as N	Straight Kjeldahl + NO_3 as N	Straight Kjeldahl + NO_3 as N	Straight Kjeldahl + NO_3 as N	Straight Kjeldahl + NO_3 as N	Modified Kjeldahl to include NO_3 as N	Nitrate (NO_3) as N	Modified Kjeldahl to include NO_3 as N
10	*11*	*12*	*13*	*14*	*15*	*16*†	*17*†	*18*
						.058	*.011*‡	
8*B*	.072	.059	.051	.071	.059	.051	*.003*	.042
						.050	*.004*	
	.002	*.005*	*.005*	*.014*	*.008*	.057	*.001*	*.001*
						Mean, .054	Mean, *.005*	
						.045	*.003*	
						.055	*.012*	
9*B*	.051	.042	.038	.057	.049	.043	*.001*	.036
						.044	*.001*	
	.000	*.002*	*.002*	*.006*	*.009*	Mean, .047	Mean, *.004*	*.000*
						.081	*.008*	
						.089	*.017*	
10*B*	.099	.072	.070	.086	.112	.071	*.001*	.065
						.073	*.002*	
	.002	*.002*	*.004*	*.010*	*.026*	Mean, .078	Mean, *.007*	*.001*
11*B*	.074	.068	.075					
	.002	*.005*	*.013*					
						.047	*.004*	
12*B*	.053	.047	.043	.055	.072	.065	*.017*	.039
						.045	*.001*	
						.046	*.001*	
	.001	*.002*	*.003*	*.008*	*.018*	Mean, .051	Mean, *.006*	*.000*
						.063	*.004*	
						.066	*.012*	
14*B*	.072	.063	.061	.079	.083	.058	*.001*	.054
						.061	*.003*	
	.001	*.002*	*.005*	*.012*	*.015*	Mean, .062	Mean, .005	*.000*

* Data are from composite samples from entire container, except in columns 7, 8, 16, and 17.

† Four samples were taken and separately analyzed in 1926; in this table the first sample listed for each soil is from the upper north center of the tank, the second from the upper south center, the third from the lower north center, and the fourth from the lower south center.

‡ All figures in italics are nitrate (NO_3) expressed as percentages of nitrogen (N) in the water-free soil.

corresponding composites of 1919. In these cases the apparent increases of nitrogen content, whether inferred from the mean or from the individual determinations of 1926, are too small anyway to have any important effect on the conclusions presented in this paper.

One other point remains to be considered before attempting to draw further conclusions. This has to do with the adequacy of the straight Kjeldahl method, which it is generally recognized may give higher figures for non-nitrate nitrogen than the true values when the sample contains appreciable amounts of nitrate nitrogen. The totals obtained by adding the figures for the separately determined nitrate nitrogen to those obtained by the straight Kjeldahl method must, therefore, be regarded as maximum values if nitrates are present in substantial amounts. It will be observed that the amount of nitrate nitrogen in the continuously cropped soils was generally of small magnitude (0.001 to 0.002 per cent), being the same as, or less than, the differences between duplicate soils (cf. cols. 2 and 11, table 6) previously noted. In the case of the fallowed soils, however, the treatment had resulted in the accumulation of large amounts of nitrate in 1918 and 1919. The figures for these years (compare cols. 11, 12, and 13, table 6), therefore, must minimize the very substantial decline in total nitrogen which they indicate to be the result of the treatment and which will be considered at greater length below.

Losses of Total Nitrogen from Cropped and Fallowed Soils

The greatest change in total nitrogen content occurred between 1915 and 1919 in both the cropped and fallowed soils. The summary in table 7 shows that every cropped soil lost in its content of total nitrogen, the smallest loss being 0.012 per cent for soil 9. This loss is three times the maximum difference observed in any of the soils as a result of the analyses of composites from duplicate tanks (1800 lbs. each) in 1915 (cf. cols. 2 and 11, table 6).

With the single exception of soil 11, all of the fallowed soils show declines during the same period of a similar order of magnitude but generally of small absolute amounts. Here again, the results appear to be significant and there can be little doubt but that the apparent losses are real. In the case of the only fallowed soil which shows no decline in nitrogen content (soil 11), it will be observed that there was an extraordinary accumulation of nitrate nitrogen in 1919 (table 6), which may have affected the determination and given a false (high) value for total nitrogen in that year.

The consistency of behavior of the cropped and fallowed soils with the exception just noted, suggests at once that the presence or absence of a crop is a minor factor in determining nitrogen losses under the conditions of intensive cultivation and the continuous maintenance of the water supply throughout the year. If it be recalled that before the inception of the present experiments, most of these soils had had a long history of intensive cropping (table 1) when they might have been expected to have attained, or to be approaching, nitrogen equilibrium

TABLE 7

LOSSES OF NITROGEN FROM CROPPED AND FALLOWED SOILS MAINTAINED IN A MOIST CONDITION THROUGHOUT THE YEAR

(Expressed as percentage of nitrogen (N) in the water-free soil.)

Soil No.	Soils cropped (1915–1919 incl.)			Soils fallowed (1916-1919 incl.)		
	Total nitrogen (1915)	Loss of total nitrogen (1915–1919 incl.)		Total nitrogen (1915)	Loss of total nitrogen (1915–1919 incl.)	
1	.147	.042	(29)*	.145	.027	(19)
2	.137	.036	(26)	.138	.022	(16)
3	.180	.036	(20)	.178	.027	(15)
4	.129	.022	(17)	.128	.011	(9)
5	.145	.027	(19)	.145	.014	(10)
6	.143	.033	(23)	.142	.028	(20)
7	.075	.022	(29)	.072	.009	(12)
8	.075	.029	(39)	.072	.021	(28)
9	.051	.012	(24)	.051	.013	(25)
10	.095	.031	(33)	.099	.029	(31)
11	.077	.025	(32)	.074	.001 (gain)	(1)
12	.055	.017	(31)	.053	.010	(18)
14	.071	.022	(31)	.072	.011	(15)

* Figures in parentheses are the losses expressed as percentages of the respective total nitrogen contents in 1915.

at a relatively slow rate, the changes observed are very striking. It is true that during the first three of the four years under discussion here, many of the soils produced crops which were probably much larger than they had been producing before the experiment began, but inasmuch as the fallowed soils also suffered large losses of total nitrogen, it seems reasonable to assign a dominant role in causing such losses to the differences in treatment under the experimental conditions as compared with those of field practice, which have modified the microbiological factor to the detriment of the nitrogen content. To aid in evaluating the effect of crop withdrawals upon the soil nitrogen, table 8 is presented.

Here, it will be observed, the absolute losses from cropped soils are very much greater than withdrawals by crops. When the crop withdrawals are deducted from the total losses, the figures are, for the most part, of the same general magnitude as those from the uncropped soils. This indicates that the losses of total nitrogen in soils under crop, other than those due to crop withdrawal, are mainly due to biological reduction in the soil itself and not to direct losses from the plant incident to its metabolic processes (gaseous nitrogen or effloresced salts).[13] Moreover, under the conditions of this period when soils were in a relatively good state of fertility and the moisture content kept up to optimum throughout the year, such losses appear to be inevitable and of substantial magnitude.

TABLE 8

SUMMARY OF CHANGES IN NITROGEN CONTENT OF CROPPED AND FALLOWED SOILS MAINTAINED IN A MOIST CONDITION THROUGHOUT THE YEAR

Soil No.	Soils cropped (1915-1919 inclusive)				Soils fallowed (1916-1919 inclusive)		
	Loss during period per cent water-free soil	Absolute loss from 1600 lbs. of soil,* grams	Withdrawn by crops,† grams	Loss additional to crop withdrawal, grams (col. *3* minus col. *4*)	Loss during period, per cent water-free soil	Absolute loss from 1600 lbs. of soil, grams	Difference between losses from cropped and fallowed soils, grams (col. 5 minus col. 7)
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
1	.042	305	75	230	.027	196	+34
2	.036	261	67	194	.022	160	+34
3	.036	261	40	221	.027	196	+25
4	.022	160	65	95	.011	80	+15
5	.027	196	74	122	.014	102	+20
6	.033	240	85	155	.028	203	−48
7	.022	160	57	103	.009	65	+38
8	.029	211	101	110	.021	152	−42
9	.012	87	39	48	.013	94	−46
10	.031	225	84	141	.029	211	−70
11	.025	181	69	112	.001‡ (gain)	7 (gain)	+105
12	.017	123	38	85	.010	73	+12
14	.022	160	51	109	.011	80	+29
Mean of all soils		198	65	133		124	+ 9

* The weight of soil used is an approximate value, on the water-free basis, actual weights not being available.

† The percentages of nitrogen used in computing the values in col. *4* are those obtained from the crop from each soil in 1915.

‡ See text page 280 for discussion of the variation of this figure.

The importance of this may be better appreciated by converting the figures into the terms of field practice. On this basis the mean loss of 133 grams per tank from cropped soils after allowing for crop withdrawals, is equivalent to 1,023 pounds per acre to a depth

[13] Small losses of metabolic nitrogen are, of course, not precluded.

of 18 in. or 511 pounds per acre to a depth of 9 in. for the period June, 1915, to November, 1919, the loss per crop season to a depth of 9 in. being about 100 pounds. Lipman and Blair[8] found losses from a light loam soil to be about 1,000 pounds (excluding crop withdrawals) per acre to a depth of 10 in. in ten years, which gives approximately the same mean annual loss as that recorded above. Their investigations also showed that after an additional ten-year period, a point of equilibrium between nitrogen income (nitrogen fixed) and outgo (withdrawals by plants) had very nearly been reached. In the present experiment, it is not certain that equilibrium had come about in the cropped soils for the conditions of the period under discussion, since, with one exception, the observed nitrogen contents in 1919 were definitely lower than those of the year immediately preceding (compare cols. 3 and 4, table 6) and the subsequent data are not adequate to determine this point because the conditions of the experiment were changed at the close of 1919 by the discontinuance of irrigation between cropping seasons.

Evidences of Nitrogen Fixation

Subsequent to 1919, there is only one case (soil 8) of an apparent loss of total nitrogen for the period as a whole, sufficiently great to suggest an actual loss, in any of the continuously cropped soils (compare cols. 4 and 9, table 6). On the contrary, a number of soils show increases in 1927 over the values for 1919. Even if these apparent gains are regarded as assignable to experimental errors of sampling and analysis, the nitrogen actually removed in the seven crops which were taken off in the interim must still be accounted for. It seems apparent, therefore, that the nitrogen requirements of the crops on the present low scale of production in all but the one case noted above, are being approximately or fully met by nitrogen fixation and that the changed conditions subsequent to 1919 (withholding water between seasons) is not unfavorable to and may have been an important factor in facilitating the process. A result so nearly unanimous in soils of different kinds and varied crop history, indicates that the continued fairly uniform production of soils which has so often been observed after flush production is over, may be dependent upon nitrogen fixation for its perpetuation.

The evidence with respect to fixation in the fallowed soils is of course limited to the period of actual fallowing, i.e., from 1916 to January, 1926, inasmuch as a crop was grown on this group of soils in 1915 and again annually since 1926. As shown previously, there was in the period 1915 to 1919 a rapid decline in total nitrogen. Subsequent to 1919 and until January, 1926, the annual cultivation was discontinued and no water was permitted access to the soils at any time. There was thus a progressive drying out of all soils, so that at the end of the seven years the moisture contents had been reduced to low levels (from 6.5 to 10 per cent for the heavy soils and 4.5 to 7 per cent for the light soils). During this period, two of the three observations made for each soil invariably gave higher figures for total nitrogen than those of 1919 (compare col. 13 with cols. 14, 15, and 16, table 6) and usually all these observations testify to the reality of the gains of fixed nitrogen. These gains, in numerous instances, were greater than the losses of the period 1915–1919, but cannot be regarded as a very stable or permanent acquisition, since the maximum amount is frequently observed before the end of the period of fallowing. Thus in 1926, many of the soils had less total nitrogen than was observed in 1923 or 1924, and this without further changes in the conditions other than those due to the gradual drying out of the soil. The 1926 figures are absolutely consistent in that all soils showed higher figures at that time than the corresponding figures for 1919. Some of the differences shown are unquestionably due to experimental errors of analysis and sampling, but the final net gains in five of the six heavy soils and three of the six light soils (compare cols. 13 and 16, table 6) may fairly be regarded as significant and substantial results of the treatment.

The condition of these soils during the initial period (1915–1919) is not analogous to that of any situation likely to occur in nature or in farming practice. During the period 1920–1926, however, their condition was substantially that of virgin soils of arid regions, where no green vegetation exists or where precipitation is only sufficient to produce a light spring growth of native plants or to maintain only the most drought-resistant perennials.[14]

A rigid adherence to the conditions of these experiments, while favorable to the accumulations of nitrogen, is, of course, incompatible with the continued economical use of land. It may not be superfluous, however, to point out that the nearer these conditions are approached in farming practice, the less will be the tendency for the soil to lose its nitrogen and the greater the probability that nitrogen fixation will postpone the evil day when nitrogen fertilizers must be applied. The limited cultivation and minimum application of

[14] These soils were kept clear of weeds at all times.

TABLE 9

CARBON (C) AND NITROGEN (N) IN SOILS*

Soil No.	Cultural treatment	Per cent of water-free soil		Ratio
		C	N	$\frac{C}{N}$
1	None (stored)	1.38	.144	9.58
	Cropped	1.14	.112	10.18
	Fallowed	1.19	.117	10.17
	None (stored)	1.29	.137	9.42
2	Cropped	1.03	.109	9.45
	Fallowed	1.07	.110	9.73
	None (stored)	1.72	.178	9.66
3	Cropped	1.57	.150	10.47
	Fallowed	1.63	.156	10.45
	None (stored)	1.28	.128	10.00
4	Cropped	1.02	.109	9.36
	Fallowed	1.02	.104	9.81
	None (stored)	1.49	.144	10.35
5	Cropped	1.21	.117	10.34
	Fallowed	1.25	.120	10.42
	None (stored)	1.41	.142	9.93
6	Cropped	1.12	.118	9.49
	Fallowed	1.18	.116	10.17
	None (stored)	0.59	.073	8.08
7	Cropped	0.43	.052	8.27
	Fallowed	0.44	.054	8.15
	None (stored)	0.51	.072	7.08
8	Cropped	0.35	.038	9.21
	Fallowed	0.39	.042	9.29
	None (stored)	0.37	.051	7.26
9	Cropped	0.28	.036	7.78
	Fallowed	0.28	.036	7.78
	None (stored)	0.94	.095	9.89
10	Cropped	0.73	.063	11.59
	Fallowed	0.74	.065	11.39
	None (stored)	0.55	.074	7.43
11	Cropped	0.43	.052	8.27
	Fallowed	Discontinued		
	None (stored)	0 44	.053	8.30
12	Cropped	0.37	.038	9.74
	Fallowed	0.38	.039	9.74
	None (stored)	0.70	.071	9.86
14	Cropped	0.58	.051	11.37
	Fallowed	0.57	.054	10.56

* All determinations made on cropped and fallowed soils in 1927.
The determinations of nitrogen in the original soils were made in 1915, those of carbon were made in 1927 on samples which had been stored in glass bottles since 1915.

water, which are the essential conditions, are only possible in otherwise fertile soils of regions of deficient rainfall where irrigation is practiced. It can hardly be doubted that deviation from these conditions is a frequent cause of the unduly rapid decline in nitrogen supply and in the crop-producing power of soils.

Carbon Content of Soils

The relation between the liquid phase and the capacity of the soil to form nitrates is so intimate as to clearly justify the studies of the nitrogen economy presented above. Carbon, also, as a source of CO_2, H_2CO_3, and HCO_3 by biological oxidation, doubtless has an important function in determining the concentration of the liquid phase in many soils.[2] It is equally obvious, however, that determinations of carbonates and bicarbonates in the liquid phase of acid or neutral soils cannot measure the extent of the influences of CO_2 in dissolving solid phase soil components. The value of the carbon content as a soil constituent thus becomes a matter of inference from the statistical interpretation of empirical data and is subject to all the difficulties characteristic of that method of procedure. On these accounts, we have not felt warranted in following the fluctuations of carbon content in the present studies. Some observations of this factor have, however, been carried out and are presented here primarily for purposes of record.

The only generalization worthy of note is that all soils, cropped and fallowed, have lost carbon and that for the most part the relative loss is about the same as that of the total nitrogen content.

THE LIQUID PHASE OF CROPPED AND FALLOWED SOILS

The special studies emanating from this laboratory from time to time have shown that the results of water extractions and displacements generally afford a fairly accurate measure of the content of the liquid phase of neutral and alkaline soils and reflect what may be termed the 'condition' of the soil. Certainly, in the present state of our knowledge, it can hardly be controverted that high concentrations of dissolved constituents (not including sodium salts, which owe their presence primarily to causes other than the biological activity of the soil) usually connote a high degree of fertility. That the converse of this proposition does not necessarily hold and that soils of low concentration in the liquid phase are often very fertile, may merely mean that high concentrations are compensated for, in terms of plant growth, by a high rate of formation of biologically produced constituents, such as nitrate, sulfate, and bicarbonate; by excretion of carbonic acid or organic acids from the plant roots; and by a solid phase which reacts readily with such agents, releasing important constituents from the solid phase *pari passu* with the plant's absorption.

This idea is confirmed by the fact that in culture solution experiments, *almost* as good growth is obtained from solutions of low concentration *if continuously maintained,* as from *high concentrations also continuously maintained.* The results of repeated experiments of this kind have convinced us that in such cases, the differences between yields obtained from solutions of high and those from solutions of fairly low concentrations would be negligible, if it were practicable to rigorously maintain the concentrations of the weak solutions. This we have been unable to do, with the facilities at our command, using solutions as low as 150 p.p.m. of total solutes. The very slight inferiority of yields obtained with dilute solutions as compared with those from more concentrated solutions, appears to warrant the belief expressed above.

The great value of initially high concentrations must not, however, be minimized, as is indicated by culture solution experiments in which plants are allowed to develop in solutions of high concentration, and transferred for the greater part of the season to solutions of low concentration without loss of yield. This, of course, means that the rapid absorption induced by the higher concentration makes up for the diminished rate of intake from the weaker solution. The experimental data thus suggest that high initial concentration with a low rate of formation of solutes during the period of plant growth, and low initial concentrations with a high rate of formation of solutes, may be equally effective in soils in the field.

It is, however, and with reason, contended that a part of the substances which are absorbed by the plant may not enter into true solution in the sense referred to above, but that the soil colloids and root hairs form an intimate union without a discrete intervening aqueous layer.[5] That such a relation exists and may account for a part of the intake of the plant cannot safely be denied, but the experiments upon which this theory of absorption are largely based and which show that an actual contact of root hair and soil particle is advantageous to the plant can be explained in other ways, the most obvious of which is the effect of a higher partial pressure of CO_2 and greater concentrations of biologically produced acids at the surface of the absorbing tissue than exists in the body of the soil moisture. By virtue of the enhanced but highly localized hydrogen ion concentration thus developed, substances may enter into a true solution and be absorbed by the plant before diffusing into the mass of the soil water.

Such an effect obviously limits the conclusions to be drawn from studies of the liquid phase and is competent to account for the adequate absorption of individual constituents sometimes obtained (together with correspondingly good growth when the particular constituent is a limiting factor) from soils in which the concentration of such constituents in the liquid phase is lower than that of culture solutions yielding equal growth.[10] A certain quota of each constituent derived from the solid phase may be assumed to be absorbed by the plant so immediately in point of time or in distance from the point of origin that its presence is not reflected in the solutions obtained from soils. This quota of each of several constituents unquestionably forms a relatively large proportion of the total amount absorbed by the plant from soils which at no time carry high concentrations of such constituents in their liquid phase, as in typical acid soils of low concentration. Although the apparent contribution from the solid phase must be of smaller magnitude and of relatively less importance to the welfare of the plant in biologically active soils of neutral or slightly alkaline reaction, which normally carry high concentrations, it cannot safely be disregarded except in the case of soils in which the amounts of the given constituent in solution at the beginning of the season are sufficiently great to supply the entire seasonal requirement of the crop.

Unfortunately for the adequacy of soil solution studies taken alone, the two elements supplied by the mineralized solid phase which are most frequently required as fertilizers, i.e., phosphate and potassium, are the very ones which show the greatest disproportion between the crop's seasonal requirement and the amount actually in solution in the soil. It may be asserted dogmatically that soils in general do not contain in solution, at any one time, more than a very small proportion of the seasonal requirement of the crop for phosphate and that the successive increments absorbed by the plant from time to time must be replaced to permit of further absorption, or that the kind of absorption must be primarily of the type discussed above, which is not ascertainable by examination of the liquid phase. With respect to potassium, on the other hand, the amount present in the liquid phase more nearly approaches the amount absorbed by a normal crop, so that relatively much less need enter solution during the growing season to satisfy the crop's requirement. When the potassium content of the aqueous phase in any soil is of this magnitude, it is reasonably safe to assert that this element is not likely to be a limiting factor in the growth of plants on that soil. Unfortunately, and in spite of the occurrence of large quantities of dissolved potassium in many soils, there appear to be many exceptions, and recent work in this laboratory suggests that these are far more numerous than was formerly supposed, so that here also the correlation between growth and absorption on the one hand, and concentration of potassium in the liquid phase of the soil, on the other, may fail to hold.

It thus becomes obvious that studies directed toward the determination of the phosphate fertilizer requirements of practically all soils must be based upon other criteria[15] than those afforded by examinations of the liquid phase and that the same limitation also applies to potassium in many soils. Since nitrate is the only other soil constituent which is normally of special importance in this relation, it is easy to assume that the value of the quantitative examination of the liquid phase is limited to what it may reveal as to the amount or rate of formation of this constituent. It must be emphasized, however, that while nitrate has a superior importance *per se,* it is only one of several of the normal products of biological oxidation in soils and it is obvious that these other products, notably sulfate and bicarbonate (or carbonate in alkaline soils) must have an important effect in holding cations in solution or in causing bases to dissolve in the water of the soil. The sum of the equivalents of these anions, or what is the same thing, that of the cations in equilibrium therewith, thus becomes a measure of the biological efficiency of the soil in producing or maintaining the concentration of the liquid phase. Neither the magnitude nor the relative proportions of the various anions, however, affords a basis for forecasting or estimating the relative proportions of the different bases which may enter into solution in a particular soil. In studies of the physiological efficiency of different soils or of the effect of given conditions or treatment thereon, it is, of course, necessary to determine all individual ions.

The data to be discussed embrace the evidence from recent results of the intensive study of displaced solutions and 1 to 1 extracts, as

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[15] Burd has elsewhere ventured to suggest appropriate methods of attacking this problem.[(3)]

to the nature of the liquid phase of the soils that were considered from another point of view in the first section of this paper. As stated before, Stewart made a similar study of these soils as they existed in 1915–1917, using, for the most part, 1 to 5 water extracts. Later Burd and Martin[4] considered the effects of continuous cropping and fallowing for eight years upon some of these soils (7 to 14), as inferred from displaced solutions. At the time of this latter study, the concrete evidence as to the effects of continuous fallowing upon the growth of succeeding crops did not exist. Since then, however, the previously fallowed soils have been cropped for four seasons, (1926–1929 inclusive), a period sufficiently long to reflect the effects of the former treatment upon crop yields and the effect of this growth upon the soils.

At present, then, data from two sets (originally duplicate) representing thirteen soils are available. One of these sets has been continuously cropped for fourteen years (1915–1928 inclusive), and one of them was continuously fallowed for ten years (1916–1925 inclusive), and cropped for four years (1926–1929 inclusive).

It has been shown (table 3) that the continuously cropped soils had declined 55 and 67 per cent in producing capacity for the 'heavy' and 'light' soils, respectively, as inferred from the yields of 1916–1917 and 1926–1927 (see page 265). This decline was accompanied by a significant decrease (table 6) in total nitrogen and in nitrate level. It has also been shown (table 5) that nine of the twelve soils fallowed from 1916–1925, inclusive, were much more productive in the period 1926–1927 than were their cropped duplicates in 1916 and 1917, and that the remaining three soils gave about the same yields in the later period as those of their continuously cropped duplicates in the earlier. During the interval between the two periods, considered as an entirety, the losses of total nitrogen from the fallowed soils were, in general, somewhat less than those from the continuously cropped soils, a result caused, in part, by the withdrawal from the system of the nitrogen used by the crop in the cropped soils and in part to the exceptionally favorable conditions for nitrogen fixation in the fallowed soils during the period 1919 to 1926. The nitrate content of the fallowed soils had, moreover, increased enormously (table 6) and comprised a large proportion of the total nitrogen at the end of the period of fallowing.

The numerous studies of the effect of varied proportions of water in extracting soils, carried out in this and other laboratories, make it perfectly clear that the proportion of water to soil is immaterial in the case of solutes which are so soluble and, at the same time, so small in amount, that they may be deemed to be at all times completely dissolved in the water of the soil, as it exists in place. This obviously applies to nitrate ion, which can be determined in unit weight of soil and expressed in terms of *concentration in the soil water for any soil moisture content.* The amount of water involved in the extraction of phosphate also is relatively unimportant for the reason that the concentration of that ion tends to remain relatively constant (the amount dissolved at equilibrium being apparently in direct proportion to the amount of water used), and is not greatly affected by concurrent changes in the concentrations of other ions at these dilutions. The concentration of the phosphate in the water extract may thus be assumed to be the same as that of the liquid phase of the soil in place.

The solubility of all of the other ions originating in the solid phase is substantially affected by varying the proportion of water to soil. The experimental data indicate that increasing the amount of water increases the amount of the ions in question, but not in any constant ratio to the amount of water involved. There is thus no exact basis for computing the concentration of such ions in the liquid phase from the data obtained by water extraction. The amounts of such ions found in the water extracts must represent maxima which vary with the type of soil minerals from which the given constituent is derived, and with the concentration of other ions present in solution and affecting the equilibrium. For all such ions, it is evident that the deviation from the truth will be less with each reduction in the proportion of water to soil and will disappear only when no excess of water is used. This, in effect, means that a displaced solution, which involves no excess of water, represents the only precise measure of such ions. On the other hand, the experimental evidence indicates that the deviation from the truth may not be very large if relatively small proportions of water are used and suggests that the use of water extraction with minimal proportions of water to soil may be justifiable in the case of soils which cannot be displaced because of their highly colloidal character. In the present work, we have used both methods as possible or convenient and shall discuss the limitations and significance of water extraction below.

As stated in the footnote to table 10, the cropped soils were sampled and examined in May, 1926, eight months after the last preceding crop had been removed. Any temporary effect of the recent crop is thus eliminated, and the data may be considered as representing the condition brought about by the sum total of the effects, direct and indirect, of all previous crops. For obvious reasons, the fallowed soils were sampled and examined on the same date as the cropped soils.

Since our aim is to show whether or not, and to what extent, the liquid phase has been modified by the treatment, the sampling and analysis of the untreated (neither cropped nor fallowed) soils should have been carried out in May, 1916, when the difference in cultural treatment was inaugurated. While such data are available, as reported by Stewart,[11] they were obtained by the 1 to 5 water extraction method and are not comparable with the present data, obtained by methods which eliminate to a great extent the defects of the older procedure.

In the present report, therefore, we have preferred to use as the basis for inferring the original condition of the untreated soils, more recent analyses by the present methods of portions of the original soils which had been stored in the air-dry condition since May, 1915. We realize that such data are not unimpeachable, inasmuch as, even in their air-dry condition, the stored soils may have become modified to some extent in their capacity to produce solutes, or may have accumulated more soluble material than they actually contained at the time the experiment was started. However, the evidence thus obtained, when compared with the similar evidence obtained from the cropped and fallowed soils, leads us to believe that, while the figures from the stored soils are very possibly higher than those which would have been obtained from them if the sampling and analysis had been made at the proper time by the present methods, they are probably not significantly different. The reader will, of course, have an opportunity to form his own judgment on this point, after considering the data and subsequent discussion.

Comparison of Displaced Solutions and 1 to 1 Extracts

In the first section of this paper, it was pointed out that the soils considered herein could be classified in two groups with respect to texture and colloidal properties, soils 1 to 6, inclusive, representing the heavier, and soils 7 to 14, the lighter group. We have not found it feasible to displace the heavy soils because the time necessary to obtain adequate quantities of solution for examination is long enough to permit appreciable reduction of nitrates, and since these comprise such a large proportion of the total solutes present, an erroneous impression of the concentration of the water of the soil in place would thus be given.

If all of the soils had been capable of displacement, that method would have been relied upon entirely in procuring the data from both sets of soils. Since this was not the case, the results of displacement and of water extraction of the light soils in the cropped and fallowed conditions[16] are both presented in order to justify, to the extent that it is justifiable, the use of water extraction on the heavy soils.

To put the results of water extraction and displacement on a uniform basis, it was obviously necessary to compute the water extraction data in terms of concentration of the water of the soil at the moisture content of the soil at the time the comparable displacement was performed. Referring to table 10, it will be observed that with minor exceptions, the results obtained by water extraction for the various bases and for the quantitatively important anions, nitrate and sulfate, are somewhat higher than those obtained by displacement. There is, however, not a single instance where the results by either method taken alone do not show lower figures in the cropped soils than in the fallowed soils. Stating it differently, the same conclusions as to differences in the ability of cropped and fallowed soils to accumulate solutes could be drawn from either set of data.

It is evident that whatever the texture of a soil may be, the general tendency to obtain higher results by water extraction than by displacement will always exist; but that the discrepancy is not very large in the case of the lighter soils seems sufficiently obvious from the results just discussed. Whether or not the discrepancy would be larger or smaller in heavy soils than in light soils, or absolutely larger or absolutely small in heavy soils, is not revealed by the data presented here. In this relation, it would appear to be significant that the differences shown by water extraction of the cropped and fallowed soils of the heavy group are of the same order as those shown in the light group by either method. We conclude, therefore, that where differences shown by water extraction of different soils, or of given soils which have been variously treated, are of considerable magnitude, as in most of the cases discussed herein, equal confidence may be placed in the data obtained by either method.

The data in table 10 are presented solely for the purpose of showing the differences in the liquid phase resulting from the cultural treatments, and not for comparing the different soils with each other nor relating the concentration of individual soils to their crop-producing power.

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[16] The omission of water extractions of the stored soils in the light group is merely due to the fact that additional data were not deemed essential to the comparison of the two methods.

TABLE 10

DISPLACED SOLUTIONS AND WATER EXTRACTS (1 TO 1) OF STORED (ORIGINAL SOIL), OF CROPPED (1915–1925) AND OF FALLOWED (1916–1925) SOILS*

Soil No.	Cultural treatment	Moisture (per cent)	Parts per million of the water of the soil													
			NO_3		SO_4		PO_4†		Ca		Mg		Na		K	
			Displ. solution	Extract	Displ. solution	Extract	Displ. solution	Extract	Displ. solution	Extract	Displ. solution	Extract	Displ. solution	Extract	Displ. solution	Extract
1	None (stored)	19.9	....	1,105	....	335	....	0.6	....	210	....	226	....	101	....	56
	Cropped		....	210	....	549	....	0.5	....	118	....	142	....	51	....	19
	Fallowed		....	2,595	....	951	....	0.8	....	419	....	439	....	141	....	81
2	None (stored)	17.1	....	2,083	....	447	....	0.5	....	515	....	257	....	121	....	189
	Cropped		....	274	....	603	....	0.3	....	188	....	107	....	31	....	43
	Fallowed		....	2,498	....	1,033	....	0.6	....	645	....	335	....	150	....	179
3	None (stored)	18.3	....	1,513	....	446	....	1.0	....	478	....	205	....	121	....	138
	Cropped		....	212	....	615	....	0.6	....	175	....	110	....	56	....	46
	Fallowed		....	1,860	....	1,066	....	1.1	....	531	....	263	....	174	....	116
4	None (stored)	14.9	....	1,514	....	411	....	1.6	....	503	....	200	....	137	....	114
	Cropped		....	268	....	663	....	0.6	....	266	....	133	....	57	....	26
	Fallowed		....	3.317	....	1,136	....	1.4	....	1,022	....	377	....	160	....	143
5	None (stored)	16.7	....	665	....	725	....	4.8	....	455	....	170	....	155	....	105
	Cropped		....	280	....	615	....	2.5	....	294	....	100	....	36	....	29
	Fallowed		....	2,775	....	950	....	4.9	....	865	....	265	....	85	....	140
6	None (stored)	20.0	....	956	....	232	....	0.4	....	232	....	152	....	224	....	24
	Cropped		....	240	....	666	....	0.4	....	144	....	94	....	80	....	19
	Fallowed		....	1,508	....	672	....	0.4	....	364	....	276	....	196	....	52

* The cropped and fallowed soils were sampled and examined in May, 1926. The stored soils which had been in the air-dry condition continuously for the entire period of the experiment were sampled, moistened, and examined as follows: soils 7 to 14 in May, 1923, and soils 1 to 6 in September, 1929.

† PO_4 expressed as parts per million of the displaced solution and extract, respectively.

TABLE 10 (*Concluded*)

Soil No.	Cultural treatment	Moisture (per cent)	NO_3 Displ. solution	NO_3 Extract	SO_4 Displ. solution	SO_4 Extract	PO_4† Displ. solution	PO_4† Extract	Ca Displ. solution	Ca Extract	Mg Displ. solution	Mg Extract	Na Displ. solution	Na Extract	K Displ. solution	K Extract
			Parts per million of the water of the soil													
7	None (stored)	15.6	1,508	....	189	....	3.3	....	562	....	115	....	126	....	40	....
	Cropped		377	391	649	719	0.5	0.4	300	333	62	81	38	70	9	38
	Fallowed		2,156	2,860	732	924	1.7	1.2	789	778	104	222	75	259	34	81
8	None (stored)	14.8	2,156	....	446	....	7.2	....	532	....	202	....	154	....	154	....
	Cropped		230	338	410	535	1.3	1.6	165	264	43	70	6	23	7	37
	Fallowed		1,852	2,132	701	816	5.7	6.1	621	707	139	236	57	103	77	172
9	None (stored)	15.0	688	....	186	....	2.9	....	384	....	76	....	89	....	21	....
	Cropped		161	209	525	606	1.1	0.6	231	276	36	68	18	40	7	31
	Fallowed		1,116	1,261	577	722	1.2	1.8	520	608	82	131	46	63	20	136
10	None (stored)	17.9	975	....	154	....	4.0	....	375	....	95	....	120	....	93	....
	Cropped		286	306	400	567	0.9	0.8	192	204	37	46	14	19	23	47
	Fallowed		2,967	2,830	712	803	2.9	2.1	985	922	145	138	60	106	105	459
12	None (stored)	14.8	213	....	174	....	3.1	....	148	....	49	....	53	....	31	....
	Cropped		185	199	441	582	1.3	1.2	170	221	38	73	28	49	10	24
	Fallowed		1,852	2,109	668	1,040	2.7	3.2	659	759	124	178	79	167	50	287
14	None (stored)	17.9	811	....	196	....	4.3	....	302	....	95	....	77	....	93	....
	Cropped		172	174	400	534	1.3	1.6	155	165	36	54	34	60	48	87
	Fallowed		1,659	1,372	517	624	2.6	2.8	524	468	88	147	109	119	116	298

* The cropped and fallowed soils were sampled and examined in May, 1926. The stored soils which had been in the air-dry condition continuously for the entire period of the experiment were sampled, moistened, and examined as follows: soils 7 to 14 in May, 1923, and soils 1 to 6 in September, 1929.

† PO_4 expressed as parts per million of the displaced solution and extract, respectively.

Effect of Continuous Cropping and Fallowing on the Liquid Phase

Inspection of table 10 shows lower concentrations of all constituents in cropped than in continuously fallowed soils. It also shows that the cropped soils have lower concentrations of all constituents other than sulfate, than do the stored soils with the single exception of calcium in the unproductive soil 12.

The exceptional behavior of sulfate is easily explicable, and can best be clarified by comparing it with nitrate, the only other biologically produced ion which occurs in large amounts in the liquid phase in neutral soils. Both cropping and fallowing operations, by maintaining conditions favorable to this type of oxidation, should tend toward the more or less continuous formation of nitrate and sulfate ions as long as the soils retain a supply of easily oxidizable nitrogen or sulfur compounds, but if plants are being grown, the actual amount of either constituent in the soil at any given time is necessarily affected by the amount of such constituent which is absorbed by the crop. The extraordinary capacity of the plant to absorb nitrate,[6] as compared with its limited power to accumulate sulfate, should lead us to anticipate that the sulfate content of the soil would decline at a less rapid rate than nitrate under the influence of the crop and might even tend to increase.

The present results afford two instances (soils 5 and 8) where the continued cropping to barley has not been accompanied by an apparent increase of sulfate in the soil. The exceptions noted, have, of course, no general significance and are possibly accounted for by the large crop yields of the particular soils (see table 3) in question. Moreover, it will be observed in the case of both of these soils that in their original condition they contained unusual amounts of sulfate, as compared with the other soils of their respective groups (light and heavy soils), and most of their readily oxidizable sulfur may have been converted into sulfates before the beginning of the experiments. It need hardly be stated that another kind of crop, one having exceptional ability to absorb and hence remove sulfate, might have reduced the sulfate content of any or all of the cropped soils.

The lower total cation concentrations in the cropped soils are, of course, consistent with the decline of nitrate concentration, since this is usually larger than the gain of sulfate, both absolutely and in terms of chemical equivalents, and cannot be accounted for on a basis of change in hydrogen ion concentration, inasmuch as the influence of the crop generally tends toward a shift of reaction toward the alkaline side of neutrality.[(4)]

While the apparent losses of individual cations, due to cropping, are relatively large, the amounts remaining in the cropped soils are sufficiently great, as shown by the 1 to 1 extractions, to make it unsafe to suggest that the declines in crop production shown in table 3 for all soils are influenced by low concentrations of bases in the liquid phase. Nevertheless, it appears that potassium, the cation most often required as a fertilizer, tends to decline under cropping and at a fairly rapid rate, as revealed by a method which must be assumed to give results which are higher than the truth. The results of displacement of cropped soils of light texture not only show a relatively large decline in potassium content, but in several cases give such low figures as to suggest that they may represent or approach a potassium deficiency. Thus in the case of soil 8*A*,[17] the potassium in the liquid phase would have to be replenished fourfold to supply the crop requirement in the absence of a mechanism for the absorption, by the plant, of solid-phase potassium or of potassium not ascertainable by our method. It is not suggested that the figures are proof of an actual deficiency, or that a lack of physiologically available potassium is the cause of the decline in yield of barley which has been observed in all of our soils under cropping. Indeed, we do not believe that such is the case. On the other hand, it seems a fair inference that all of these soils, under the influence of cropping, may have attained a condition such that other types of crop might find difficulty in obtaining their potassium requirement, and that a further decline of potassium in the liquid phase might limit the growth of later crops of barley. As has been elsewhere shown,[(9)] these soils have all lost from their replaceable base fractions amounts of potassium approximately equal to the estimated withdrawals by the crop, and the lowered potassium contents of the liquid phase are doubtless a reflection of this or similar changes in the solid phase and hence in themselves significant.

In the first section of this paper, attention was called to the extraordinary increase in nitrate concentration of the fallowed soils, and the relation of this to the large yields obtained when these were planted to barley in 1926 was emphasized. The present data show that these increases in nitrate concentration in the heavy soils (Nos. 1 to 6) are accompanied by a substantial increase of both calcium and

[17] The crop on soil 8*A* withdrew 4.04 grams of potassium in 1926, equivalent to approximately 27 p.p.m. in the water of the mass of soil involved (1,800 lbs. of soil at 15 per cent moisture) as against 7 p.p.m. in the displaced solution.

magnesium in all cases, with relatively smaller increases in sodium and potassium. In the light soils, the increase of cation concentration is primarily due to calcium, except in soil 12, which gained in all constituents as a result of the relatively large increase in nitrate. Magnesium, sodium, and potassium not only show no great accumulations in the latter group as a whole, but are frequently represented by decreased concentrations in the fallowed as compared with the original soils.

The most striking difference between the cropped soils as a group and the fallowed or stored soils is obviously in the nitrate concentration. It is evident that the present inability of the cropped soils to store up the amounts of nitrate which were formerly characteristic of each soil, or which would have been accumulated had no crops been grown under otherwise favorable conditions, as in fallowing, can be accounted for in many ways. Among the conditions which are the most probable causes of this difference are the partial exhaustion of nitrogen-carrying organic compounds capable of biological oxidation; an accumulation of carbohydrate material from the roots of successive generations of plants, the utilization of which by soil organisms involves the reduction of nitrate; changes in the biological flora; changes physical or chemical affecting biological oxidation indirectly.

SEASONAL FLUCTUATIONS IN CONTINUOUSLY CROPPED (DEPLETED) SOILS

In a former paper[4] evidence was presented which showed for soils which had been continuously cropped to barley for eight years and which had declined in yield to 39 and 29 per cent respectively of grain and total dry matter, that there is a seasonal decline in concentration of most constituents in the liquid phase while the crop is growing, but that such losses are made up by the beginning of the following season as a result of solution and biological processes. As there stated, ''under such circumstances, we might legitimately anticipate that whatever changes occur during a given growing season, the condition of the soil at the beginning of each season should be relatively constant. . . . . In the light of these results, there can be but little doubt that the reason why a depleted soil continues to give fairly uniform crops for many years is that it attains an equilibrium, which is a function of environmental conditions and the nature of the solid phase. The comparatively small amounts of solutes removed from year to year by the growing plants do not substantially change the composition of the solid phase, and hence cannot materially effect the equilibrium.''

That the above conclusions were sound is indicated by subsequent studies, herein reported, of the same soils (7 to 14) considered in the former paper. The reader may note (table 3) that the mean yields of these soils were 445 grams and 187 grams of total dry matter and grain, respectively, in 1923, as compared with corresponding mean yields of 401 grams and 187 grams for the period 1926–1928; so that in spite of subsequent fluctuations in the yield of individual soils, it is a fair inference that the scale of productiveness is approximately the same as that suggested by the earlier data, except as affected in given years by especially favorable seasonal conditions. That the liquid phase also remains relatively constant in composition can be verified by comparing the present data for these same soils in May, 1926, with the previously published data for April, 1923.[18]

One reservation to the latter statement must be made in that several of the soils appear to have declined still further in potassium content of the liquid phase during the period of three years between the two sets of observations. The implications of such declines have been described above (see p. 297).

Table 11 shows the seasonal decline in concentration of the group of light soils (7–14), to which attention was called in the earlier paper.[(4)] Declines of a similar order are indicated for soils 5 and 6. Soils 1–4, however, all carried relatively high concentrations at the end of the season, as compared with those at the beginning. It should be pointed out, however, that sampling at harvest time minimizes the value of the data for showing the seasonal effect because substantial nitrification usually occurs in these soils after the plant has ceased to absorb and before harvesting. This was certainly the case with respect to soils 2 and 3, which a seasonal (1926) study of nitrate fluctuations reveals as having almost exactly doubled in nitrate concentration between August 27, when the heads were fully formed, and September 25, the date of harvesting. That study showed similarly that soil 1 also increased its nitrate materially (about 30 per cent) in the same period.

It seems rather obvious that seasonal decline of concentration in the liquid phase is a rather general phenomenon, the demonstration of which may fail in given cases if the soils are not examined almost immediately after the cessation of absorption on the part of the plant. It is also obvious that any limitation in the growth of the crop induced

[18] See Table V in Burd and Martin.[(4)]

TABLE 11

DISPLACED SOLUTIONS AND WATER EXTRACTS (1 TO 1) OF CONTINUOUSLY CROPPED SOILS AT BEGINNING AND END OF TWELFTH GROWING SEASON (1926)

Soil No.	Date	Moisture, per cent	pH	Specific resistance, ohms	Parts per million of the water of the soil														
					HCO_3	NO_3		SO_4		PO_4*		Ca		Mg		Na		K	
					Displaced solution	Displaced solution	Extract	Displaced solution	Extract	Displaced solution	Extract	Displaced solution	Extract	Displaced solution	Extract	Displaced solution	Extract	Displaced solution	Extract
1	May	19.9	....	....	....	....	210	....	549	....	0.5	....	118	....	142	....	51	....	19
	Sept.		....	....	....	....	189	....	496	....	0.3	....	106	....	92	....	31	....	44
2	May	17.1	....	....	....	....	274	....	603	....	0.3	....	188	....	107	....	31	....	43
	Sept.		....	....	....	....	268	....	586	....	0.5	....	167	....	76	....	36	....	76
3	May	18.3	....	....	....	....	212	....	615	....	0.6	....	175	....	110	....	56	....	46
	Sept.		....	....	....	....	325	....	627	....	1.0	....	189	....	69	....	58	....	63
4	May	14.9	....	....	....	....	268	....	663	....	0.6	....	266	....	133	....	57	....	26
	Sept.		....	....	....	....	300	....	483	....	0.5	....	246	....	99	....	41	....	57
5	May	16.7	....	....	....	....	280	....	615	....	2.5	....	294	....	100	....	36	....	29
	Sept.		....	....	....	....	88	....	447	....	2.3	....	249	....	70	....	25	....	49
6	May	20.0	....	....	....	....	240	....	666	....	0.4	....	144	....	94	....	80	....	19
	Sept.		....	....	....	....	21	....	494	....	0.3	....	111	....	57	....	73	....	30
7	May	15.6	7.6	546	87	377	391	649	719	0.5	0.4	300	333	62	81	38	70	9	38
	Sept.		7.6	992	110	46	59	400	467	0.7	0.6	164	193	57	41	24	43	7	24
8	May	14.8	7.4	834	84	230	338	410	535	1.3	1.6	165	264	43	70	6	23	7	37
	Sept.	14.7	7.3	1,308	93	35	69	303	351	1.8	1.2	122	139	35	43	12	20	10	34
9	May	15.0	7.5	770	73	161	209	525	606	1.1	0.6	231	276	36	68	18	40	7	31
	Sept.	14.7	7.5	1,506	73	37	128	244	289	1.1	0.9	114	156	39	27	13	22	5	27
10	May	17.9	7.2	750	50	286	306	400	567	0.9	0.8	192	204	37	46	14	19	23	47
	Sept.	17.8	7.4	1,335	51	50	118	298	351	1.2	0.7	109	108	30	25	14	26	18	63
11	May	12.3	....	....	....	....	259	....	940	....	3.3	....	288	....	111	....	112	....	100
	Sept.		....	....	....	....	14	....	579	....	4.3	....	164	....	56	....	100	....	107
12	May	14.8	7.1	811	33	185	199	441	582	1.3	1.2	170	221	38	73	28	49	10	24
	Sept.	14.7	7.2	1,253	49	30	25	350	445	1.9	0.9	109	133	39	34	23	41	8	44
14	May	17.9	7.8	820	89	172	174	400	534	1.3	1.6	155	165	36	54	34	60	48	87
	Sept.	17.8	7.6	1,196	109	18	13	309	351	1.3	0.5	100	81	27	23	35	66	38	113

* PO_4 expressed as parts per million of the displaced solution and extract, respectively.

by other factors than a low concentration in the liquid phase, might decrease the absolute amounts of solutes absorbed by the crop to such an extent that there would be no lowering of the concentration in the liquid phase of some soils, the small amounts absorbed being made good by biological oxidation, if the conditions are favorable to such processes.

Decline in Concentration of Previously Fallowed Soils

When similar data from soils, the aqueous concentration of which has been built up by the fallowing process is considered, it is seen that the decline in total concentration is very marked, relatively and absolutely, the first season they are cropped, but the amounts of dissolved material remaining at the end of the season are still very considerable. (Compare data for September in tables 11 and 12), as compared with the condition in continuously cropped soils at the same period of the year.

It has been pointed out elsewhere that losses of nitrates occurring during the growing season are frequently greater than can be accounted for by the amount of nitrogen removed in the crop, even when leaching is precluded, as has been the case in all of these experiments. The present data confirm our previous conclusion on this point. For example, soil 1 (table 12), lost 1,717 p.p.m. of nitrate, equivalent to 77.5 grams of nitrogen for the entire mass of soil involved, and the crop removed 23.4 grams of nitrogen, comprising only 30 per cent of the nitrogen which has disappeared as nitrate. Soil 8 lost 1,029 p.p.m. of nitrate, equivalent to 34.8 grams of nitrogen, and the crop removed 24.3 grams, comprising 70 per cent of the nitrogen which had disappeared as nitrate. Judging by the magnitude of the losses from the other soils, it is apparent that all have lost more nitrate than was withdrawn by the crops, and it may be inferred that soils carrying high concentrations of nitrate are especially subject to such losses.

The special studies necessary to determine what became of the nitrogen represented by the decline in nitrate have not been made; and it is a matter for speculation whether it became fixed as a constituent of bacterial protein, or was lost as gaseous nitrogen, or in other ways. It may be noted, however, that the nitrogen withdrawal of the large crops obtained in the succeeding year (1927) is about 24 grams, which is equivalent to 500 p.p.m. of nitrate in the water of the soil for the amount of soil involved in each case. Since every soil

TABLE 12

DISPLACED SOLUTIONS AND WATER EXTRACTS (1 TO 1) OF PREVIOUSLY FALLOWED SOILS* AT BEGINNING AND END OF FIRST GROWING SEASON (1926)

Soil No.	Date	Moisture, per cent	pH	Specific resistance, ohms	Parts per million of the water of the soil														
					HCO_3	NO_3		SO_4		PO_4†		Ca		Mg		Na		K	
					Displaced solution	Displaced solution	Extract	Displaced solution	Extract	Displaced solution	Extract	Displaced solution	Extract	Displaced solution	Extract	Displaced solution	Extract	Displaced solution	Extract
1	May	19.7	......	....	....	....	2,626	....	961	....	0.8	....	426	....	444	....	142	....	82
	Sept.		......	....	....	....	909	....	632	....	1.1	....	169	....	180	....	65	....	72
2	May	17.7	......	....	....	....	2,394	....	991	....	0.6	....	618	....	319	....	142	....	172
	Sept.		......	....	....	....	1,342	....	776	....	0.4	....	414	....	204	....	57	....	158
3	May	18.0	......	....	....	....	1,902	....	1,089	....	1.1	....	544	....	269	....	178	....	120
	Sept.		......	....	....	....	1,053	....	766	....	0.7	....	384	....	142	....	73	....	126
4	May	14.7	......	....	....	....	3,370	....	1,154	....	1.4	....	1,037	....	382	....	161	....	146
	Sept.		......	....	....	....	2,032	....	1,017	....	1.0	....	613	....	207	....	70	....	118
5	May	14.2	......	....	....	....	3,353	....	1,150	....	4.9	....	1,045	....	322	....	101	....	168
	Sept.		......	....	....	....	2,910	....	1,121	....	3.8	....	888	....	280	....	92	....	167
6	May	18.8	......	....	....	....	1,630	....	727	....	0.4	....	392	....	297	....	213	....	57
	Sept.		......	....	....	....	575	....	792	....	0.4	....	216	....	125	....	138	....	58
7	May	14.9	7.3	306	51	2,279	3,022	774	979	1.7	1.2	834	825	110	231	79	272	36	88
	Sept.	14.5	7.6	287	57	1.324	1,272	794	1,011	1.4	1.1	596	636	111	141	70	82	23	73
8	May	15.0	6.9	240	41	1,830	2,102	693	805	5.7	6.1	614	698	137	230	56	100	76	173
	Sept.	14.4	6.9	419	46	801	794	619	754	3.3	3.5	374	381	89	119	35	52	39	114
9	May	15.1	7.4	330	63	1,104	1,250	571	716	1.2	1.8	514	602	81	128	45	59	20	135
	Sept.	14.6	7.5	815	96	166	267	421	604	1.4	1.1	216	302	36	58	22	46	13	58
10	May	18.3	6.8	167	40	2,887	2,756	693	783	2.9	2.1	958	900	141	133	58	105	102	446
	Sept.	17.7	7.1	420	51	771	605	612	751	2.2	1.6	374	346	81	83	27	27	49	134
12	May	15.3	6.8	241	28	1,781	2,036	642	1,000	2.7	3.2	634	731	119	173	76	161	48	279
	Sept.	14.7	7.0	530	57	432	390	635	850	2.5	2.2	288	300	79	86	35	39	25	90
14	May	17.9	7.4	261	57	1,659	1,371	517	626	2.6	2.8	524	468	88	146	109	119	116	297
	Sept.	17.6	7.4	440	92	618	514	608	755	2.3	2.5	314	264	81	73	62	82	79	208

* Soils cropped in 1915, fallowed 1916-1925 inclusive, and cropped in 1926.

† PO_4 expressed as parts per million of the displaced solution and extract, respectively.

TABLE 13

DISPLACED SOLUTIONS AND WATER EXTRACTS (1 TO 1) OF PREVIOUSLY FALLOWED SOILS (1916–1925) AT BEGINNING AND END OF FOURTH GROWING SEASON (1929)

Soil No.	Date	Moisture, per cent	pH	Specific resistance, ohms	Parts per million of the water of the soil: HCO_3 Displaced solution	NO_3 Displaced solution	NO_3 Extract	SO_4 Displaced solution	SO_4 Extract	PO_4* Displaced solution	PO_4* Extract	Ca Displaced solution	Ca Extract	Mg Displaced solution	Mg Extract	Na Displaced solution	Na Extract	K Displaced solution	K Extract
1	May	19.9	......	......	......	......	181	......	907	......	0.7	......	173	......	177	......	93	......	24
	Sept.		......	......	......	......	25	......	516	......	0.4	......	113	......	113	......	64	......	24
2	May	17.1	......	......	......	......	170	......	733	......	0.5	......	218	......	112	......	53	......	63
	Sept.		......	......	......	......	53	......	422	......	0.4	......	155	......	82	......	58	......	58
3	May	18.3	......	......	......	......	161	......	813	......	0.5	......	250	......	103	......	80	......	58
	Sept.		......	......	......	......	29	......	682	......	0.7	......	192	......	80	......	67	......	54
4	May	14.9	......	......	......	......	154	......	1,000	......	0.8	......	400	......	143	......	80	......	40
	Sept.		......	......	......	......	41	......	799	......	0.7	......	343	......	126	......	86	......	42
5	May	16.7	......	......	......	......	275	......	850	......	3.6	......	410	......	120	......	40	......	40
	Sept.		......	......	......	......	34	......	525	......	2.5	......	285	......	75	......	30	......	31
6	May	20.0	......	......	......	......	156	......	712	......	0.2	......	184	......	104	......	128	......	16
	Sept.		......	......	......	......	32	......	740	......	0.3	......	172	......	100	......	124	......	15
7	May	15.6	8.1	551	90	185	141	795	816	0.7	0.7	315	351	60	81	38	70	9	38
	Sept.		8.4	707	91	31	41	708	628	0.6	0.5	251	222	53	54	43	49	10	16
8	May	14.8	7.4	655	70	247	259	525	586	2.3	2.6	229	293	59	80	26	46	16	46
	Sept.		7.6	1,139	88	30	20	326	351	1.6	1.4	135	138	37	48	19	18	14	25
9	May	15.0	7.6	672	70	125	91	634	648	0.7	0.7	256	312	43	63	32	57	9	28
	Sept.		7.8	1,205	83	19	16	306	341	0.9	0.6	143	153	24	36	21	35	10	21
10	May	17.9	7.3	622	57	147	119	667	674	1.1	1.2	256	239	59	64	24	50	32	69
	Sept.		7.4	944	54	28	28	426	441	1.2	1.0	157	149	37	47	21	53	28	30
12	May	14.8	7.2	536	34	122	126	907	1,075	1.5	1.4	296	345	73	92	50	86	16	46
	Sept.		7.5	1,092	51	19	17	403	477	2.5	0.4†	131	149	35	47	28	53	13	30
14	May	17.9	8.0	649	102	82	92	658	739	1.6	1.8	217	197	53	55	46	110	50	119
	Sept.		8.3	875	109	13	15	486	505	1.4	1.4	150	119	38	32	40	87	48	92

* PO_4 expressed as parts per million of the displaced solution and extract, respectively.

† Questionable determination.

TABLE 14

DISPLACED SOLUTIONS AND WATER EXTRACTS (1 TO 1) OF PREVIOUSLY FALLOWED SOILS* BEFORE AND AFTER CROPPING FOR THREE CONSECUTIVE YEARS (1926–1928)

Soil No.	Date	Moisture, per cent	pH	Specific resistance, ohms	HCO₃ Displaced solution	NO₃ Displaced solution	NO₃ Extract	SO₄ Displaced solution	SO₄ Extract	PO₄† Displaced solution	PO₄† Extract	Ca Displaced solution	Ca Extract	Mg Displaced solution	Mg Extract	Na Displaced solution	Na Extract	K Displaced solution	K Extract
					Parts per million of the water of the soil														
1	1926	19.7	......	....	....	....	2,626	....	961	....	0.8	....	426	....	444	....	142	....	82
	1929	19.5	......	....	....	....	185	....	933	....	0.7	....	178	....	183	....	93	....	25
2	1926	17.7	......	....	....	....	2,394	....	991	....	0.6	....	618	....	319	....	142	....	172
	1929	18.6	......	....	....	....	155	....	665	....	0.5	....	198	....	99	....	49	....	55
3	1926	18.0	......	....	....	....	1,902	....	1,089	....	1.1	....	544	....	269	....	178	....	120
	1929	16.4	......	....	....	....	186	....	930	....	0.5	....	284	....	116	....	94	....	65
4	1926	14.7	......	....	....	....	3,370	....	1,154	....	1.4	....	1,037	....	382	....	161	....	146
	1929	16.3	......	....	....	....	141	....	901	....	0.8	....	360	....	131	....	72	....	36
5	1926	14.2	......	....	....	....	3,353	....	1,150	....	4.9	....	1,045	....	322	....	101	....	168
	1929	14.6	......	....	....	....	322	....	997	....	3.6	....	481	....	141	....	49	....	49
6	1926	18.8	......	....	....	....	1,630	....	727	....	0.4	....	392	....	297	....	213	....	57
	1929	19.5	......	....	....	....	160	....	737	....	0.2	....	190	....	109	....	132	....	17
7	1926	14.9	7.3	306	51	2,279	3,022	774	979	1.7	1.2	834	825	110	231	79	272	36	88
	1929	14.9	8.1	521	90	196	146	840	864	0.7	0.7	333	372	63	85	40	75	10	39
8	1926	15.0	6.9	240	41	1,830	2,102	693	805	5.7	6.1	614	698	137	230	56	100	76	173
	1929	14.5	7.4	640	70	253	268	537	603	2.3	2.6	234	302	60	85	27	47	16	46
9	1926	15.1	7.4	330	63	1,104	1,250	571	716	1.2	1.8	514	602	81	128	45	59	20	135
	1929	15.0	7.6	672	70	125	89	634	646	0.7	0.7	256	315	43	61	32	55	9	28
10	1926	18.3	6.8	167	40	2,887	2,756	693	783	2.9	2.1	958	900	141	133	58	105	102	446
	1929	18.1	7.3	631	57	145	119	658	666	1.1	1.2	252	234	58	62	24	50	32	70
12	1926	15.3	6.8	241	28	1,781	2,036	642	1,000	2.7	3.2†	634	731	119	173	76	161	48	279
	1929	14.2	7.2	511	34	128	135	950	1,126	1.5	1.4	310	359	77	97	52	93	17	46
14	1926	17.9	7.4	261	57	1,659	1,371	517	626	2.6	2.8	524	468	88	146	109	119	116	297
	1929	15.8	8.0	557	102	96	105	767	859	1.6	1.8	253	231	62	63	54	127	58	137

* Soils cropped in 1915, fallowed from 1916-1925 inclusive, and cropped 1926-1928 inclusive; these observations made in May 1926 and in May 1929.

† PO_4 expressed as parts per million of the displaced solution and extract, respectively.

with the exception of 9 and 12 contained more than this amount of nitrate at the end of 1926, after the losses were observed, it would appear that at least ten of the twelve soils had not been limited in growth for lack of nitrate, nor stood in need of nitrogen, which was possibly stored up as a result of the losses of nitrate noted.

Comparison of tables 12 and 13 shows that the soils considered just above had declined very markedly in total concentration as a result of the effect of cropping for three years and that the usual seasonal decline is in evidence during the fourth growing season, but the decline in nitrate over and above that accounted for by the plants' absorption is small. Thus: soil 1 lost 156 p.p.m. while its crop withdrew 6.6 grams of nitrogen, equivalent to 146 p.p.m. in terms of the water of the mass of soil involved, and soil 8 lost 217 p.p.m. while its crop withdrew 5.2 grams of nitrogen, equivalent to 155 p.p.m. The losses of nitrate at this stage in the progressive decline of nitrate concentration subsequent to prolonged fallowing, do not appear to greatly exceed the requirement of the crops in absolute amount, in marked contrast to the behavior shown during the first season after fallowing.

The quantitative effect upon the condition of the liquid phase, of three years' cropping of the previously fallowed soils, is shown more clearly in table 14.

The most striking change is the continued decline in nitrate concentration, but there is also a substantial loss of potassium from the liquid phase even in the short period considered. The total cation concentration is, of course, less, owing to the loss of nitrate, but is still of substantial magnitude, because of the large amount of sulfate stored up by the fallowing process.[4]

Effect of Continuous Cropping Versus Effect of Several Crops After Prolonged Fallowing

In table 15 is presented the data from the continuously cropped soils after they had been depleted by eleven years' cropping, and those from the previously fallowed soils after three crops. Comparison of the pairs of figures for each constituent shows that the concentrations of cations and sulfate are, in general, somewhat higher in the fallowed soils, than in those continuously cropped. These differences are, however, not so great as to suggest that they are fraught with much importance to subsequent crops. The concentrations shown at the end of an eleven-year period for continuously cropped soils are

TABLE 15

DISPLACED SOLUTIONS AND WATER EXTRACTS (1 TO 1) OF *A* SOILS* AFTER ELEVEN CONSECUTIVE CROPS AND OF *B* (PREVIOUSLY FALLOWED) SOILS† AFTER THREE CONSECUTIVE CROPS

Soil No.	Group	Moisture, per cent	pH	Specific resistance, ohms	Parts per million of the water of the soil														
					HCO_3	NO_3		SO_4		PO_4‡		Ca		Mg		Na		K	
					Displaced solution	Displaced solution	Extract	Displaced solution	Extract	Displaced solution	Extract	Displaced solution	Extract	Displaced solution	Extract	Displaced solution	Extract	Displaced solution	Extract
1	*A*	19.9	......	....	....	....	210	......	549	....	0.5	....	118	....	142	....	51	....	19
	B		......	....	....	....	181	....	907	....	0.7	....	173	....	177	....	93	....	24
2	*A*	17.1	......	....	....	....	274	....	603	....	0.3	....	188	....	107	....	31	....	43
	B		......	....	....	....	170	....	733	....	0.5	....	218	....	112	....	53	....	63
3	*A*	18.3	......	....	....	....	212	....	615	....	0.6	....	175	....	110	....	56	....	46
	B		......	....	....	....	161	....	813	....	0.5	....	250	....	103	....	80	....	58
4	*A*	14.9	......	....	....	....	268	....	663	....	0.6	....	266	....	133	....	57	....	26
	B		......	....	....	....	154	....	1,000	....	0.8	....	400	....	143	....	80	....	40
5	*A*	16.7	......	....	....	....	280	....	615	....	2.5	....	294	....	100	....	36	....	29
	B		......	....	....	....	275	....	850	....	3.6	....	410	....	120	....	40	....	40
6	*A*	20.0	......	....	....	....	240	....	666	....	0.4	....	144	....	94	....	80	....	19
	B		......	....	....	....	156	....	712	....	0.2	....	184	....	104	....	128	....	16
7	*A*	15.6	7.6	546	87	377	391	649	719	0.5	0.4	300	333	62	81	38	70	9	38
	B		8.1	551	90	185	141	795	816	0.7	0.7	315	351	60	81	38	70	9	38
8	*A*	14.8	7.4	834	84	230	338	410	535	1.3	1.6	165	264	43	70	6	23	7	37
	B		7.4	655	70	247	259	525	586	2.3	2.6	229	293	59	80	26	46	16	46
9	*A*	15.0	7.5	770	73	161	209	525	606	1.1	0.6	231	276	36	68	18	40	7	31
	B		7.6	672	70	125	91	634	648	0.7	0.7	256	312	43	63	32	57	9	28
10	*A*	17.9	7.2	750	50	286	306	400	567	0.9	0.8	192	204	37	46	14	19	23	47
	B		7.3	622	57	147	119	667	674	1.1	1.2	256	239	59	64	24	50	32	69
11	*A*	12.3	......	....	....	....	259	....	940	....	3.3	....	288	....	111	....	112	....	100
	B		This soil eliminated from the study in 1920.																
12	*A*	14.8	7.1	811	33	185	199	441	582	1.3	1.2	170	221	38	73	28	49	10	24
	B		7.2	536	34	122	126	906	1,075	1.5	1.4	296	345	73	92	50	86	16	46
14	*A*	17.9	7.8	820	89	172	174	400	534	1.3	1.6	155	165	36	54	34	60	48	87
	B		8.0	649	102	82	92	658	739	1.6	1.8	217	197	53	55	46	110	50	119

* Cropped 1915–1925 inclusive; observations made in May, 1926.

† Fallowed 1916–1925 inclusive and cropped 1926–1928; observations made May, 1929.

‡ PO_4 expressed as parts per million of the displaced solution and extract, respectively.

not essentially different from those of the previously fallowed soils after a much shorter period.

If similar studies of the liquid phase of the continuously cropped soils had been made in the year (1918) when they began to decline materially in crop-producing power, there can be but little doubt that they would have shown, similarly, the low concentrations now shown for the previously fallowed soils. It thus appears that a characteristic and substantial decline in concentration of the liquid phase is inevitable within a very short period (3 or 4 years), if large crops are produced on soils in a 'high' state of fertility. This decline in concentration is accompanied by a decline in crop production, but the two, in the nature of the case, are not correlated in any simple or direct manner, either for total concentrations or for those of individual constituents.

SUMMARY

Results are presented covering the systematic study of thirteen soils continuously maintained under controlled conditions for a period of eleven years.

Special attention is given to the effect upon the soil of continuous cropping, and of prolonged fallowing, followed by a period of continuous cropping.

The declines in yield and the period of the decline characteristic of continuous cropping are shown to be of the same order in soils the productive capacity of which had been enhanced by prolonged fallowing as in those which had not been so treated.

'Heavy' soils are not necessarily more productive than 'light' soils, but they tend to decline less rapidly in crop-producing capacity.

The less productive soils give a relatively greater response to fallowing than do the more productive ones.

In soils which are cultivated and kept at 'optimum' moisture throughout the year, the mean annual loss of nitrogen from the soil (other than the nitrogen removed by crops) appears to be little greater and is frequently somewhat less in cropped than in fallowed soils.

If water is withheld between seasons from continuously cropped soils which are on a low scale of production further losses of nitrogen appear to be inconsiderable and gains may occur.

If water is withheld and the soils are not cultivated, fallowed soils tend to increase in total nitrogen content as well as in nitrate by significant, and in many soils by substantial, amounts.

The ratio of carbon to nitrogen tends to be the same in continuously cropped soils as in soils which have been fallowed for a prolonged period and then cropped for several years.

A general discussion is presented, regarding: (*a*) the limitations which must be placed on the interpretation of data obtained from studies of the liquid phase; (*b*) the mechanism by which solutes enter the liquid phase; (*c*) the significance of phosphate and potassium in the liquid phase.

The relation between displaced solutions and water extracts is discussed.

The total concentration of the liquid phase is invariably decreased as a result of cropping, and is usually, but not invariably, increased by fallowing.

The sulfate concentration tends to increase in both cropped and fallowed soils. This tendency usually results in increased concentrations of sulfate in spite of plant absorption of this ion from cropped soils.

Nitrates invariably decline in cropped soils and usually increase substantially in fallowed soils.

Increases in sulfate and declines in nitrate in cropped soils thus change the general character of the liquid phase and must affect the rate of absorption by the plant of cations in equilibrium with these anions.

A significant decline in potassium concentration in a relatively short period is observed in many cropped soils.

In soils depleted as a result of cropping, there is a seasonal decline in total concentration followed by a recovery which may be fairly rapid after the plants have ceased to absorb from the soil.

Whatever their previous history, cropped soils lose more nitrate than is accounted for by the crops' absorption; the absolute losses being enormous in soils containing large amounts of nitrate.

If soils are cropped after prolonged fallowing, there is a very rapid decline in total concentration, accompanied by a decline in crop yields.

LITERATURE CITED

[1] BURD, JOHN S.
1918. Chemical criteria, crop production and physical classification in two soil classes. Soil Science 5(5):405–419.

[2] BURD, JOHN S.
1925. Relation of biological processes to cation concentrations in soils. Soil Science 20(4):269–283.

[3] BURD, JOHN S.
1927. An important aspect of soil solution research. First International Congress of Soil Science Proceedings and Papers 2:1–8.

[4] BURD, JOHN S., and J. C. MARTIN.
1924. Secular and seasonal changes in the soil solution. Soil Science 18(2):151–167.

[5] COMBER, NORMAN M.
1922. The availability of mineral plant food. Jour. Agr. Sci. 12(Pt. 4): 363–369.

[6] HOAGLAND, D. R.
1923. The absorption of ions by plants. Soil Science 16(4):225–246.

[7] HOAGLAND, D. R., and J. C. MARTIN.
1920. Effect of season and crop growth on the physical state of the soil. Jour Agr. Res. 20(5):397–404.

[8] LIPMAN, J. G., and A. W. BLAIR.
1921. Nitrogen losses under intensive cropping. Soil Science 12(1):1–19.

[9] MARTIN, J. C.
1929. Effect of crop growth on the replaceable bases in some Californian soils. Soil Science 27(2):123–136.

[10] PARKER, F. W.
1927. Soil phosphorus studies: III. Plant growth and the absorption of phosphorus from culture solutions of different phosphate concentrations. Soil Science 24(2):129–146.

[11] STEWART, GUY R.
1918. Effect of season and crop growth in modifying the soil extract. Jour. Agr. Res. 12(6):311–368.

The titles of the Technical Papers of the California Agricultural Experiment Station, Nos. 1 to 20, which HILGARDIA replaces, and copies of which may be had on application to the Publication Secretary, Agricultural Experiment Station, Berkeley, are as follows:

4. Effect of Sodium Chlorid and Calcium Chlorid upon the Growth and Composition of Young Orange Trees, by H. S. Reed and A. R. C. Haas. April, 1923.
5. Citrus Blast and Black Pit, by H. S. Fawcett, W. T. Horne, and A. F. Camp. May, 1923.
6. A Study of Deciduous Fruit Tree Rootstocks with Special Reference to Their Identification, by Myer J. Heppner. June, 1923.
7. A Study of the Darkening of Apple Tissue, by E. L. Overholser and W. V. Cruess. June, 1923.
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9. Experiments on the Reclamation of Alkali Soils by Leaching with Water and Gypsum, by P. L. Hibbard. August, 1923.
10. The Seasonal Variation of the Soil Moisture in a Walnut Grove in Relation to Hygroscopic Coefficient, by L. D. Batchelor and H. S. Reed. September, 1923.
11. Studies on the Effects of Sodium, Potassium, and Calcium on Young Orange Trees, by H. S. Reed and A. R. C. Haas. October, 1923.
12. The Effect of the Plant on the Reaction of the Culture Solution, by D. R. Hoagland. November, 1923.
14. The Respiration of Potato Tubers in Relation to the Occurrence of Blackheart, by J. P. Bennett and E. T. Bartholomew. January, 1924.
16. The Moisture Equivalent as Influenced by the Amount of Soil Used in its Determination, by F. J. Veihmeyer, O. W. Israelsen and J. P. Conrad. September, 1924.
17. Nutrient and Toxic Effects of Certain Ions on Citrus and Walnut Trees with Especial Reference to the Concentration and Ph of the Medium, by H. S. Reed and A. R. C. Haas. October, 1924.
18. Factors Influencing the Rate of Germination of Seed of Asparagus Officinalis, by H. A. Borthwick. March, 1925.
19. The Relation of the Subcutaneous Administration of Living Bacterium abortum to the Immunity and Carrier Problem of Bovine Infectious Abortion, by George H. Hart and Jacob Traum. April, 1925.
20. A Study of the Conductive Tissues in Shoots of the Bartlett Pear and the Relationship of Food Movement to Dominance of the Apical Buds, by Frank E. Gardner. April, 1925.