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Seasonal Water and Nitrate Leachings In Relation to Soil and Source of Fertilizer Nitrogen

(A Second Report on Windsor Lysimeter Series "A")

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Connecticut
Agricultural Experiment Station
New Haven

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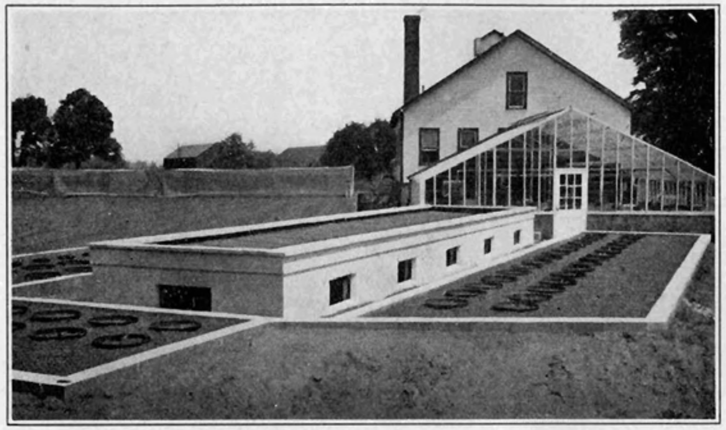

FIGURE 1. Windsor lysimeters, exterior view, 1929.

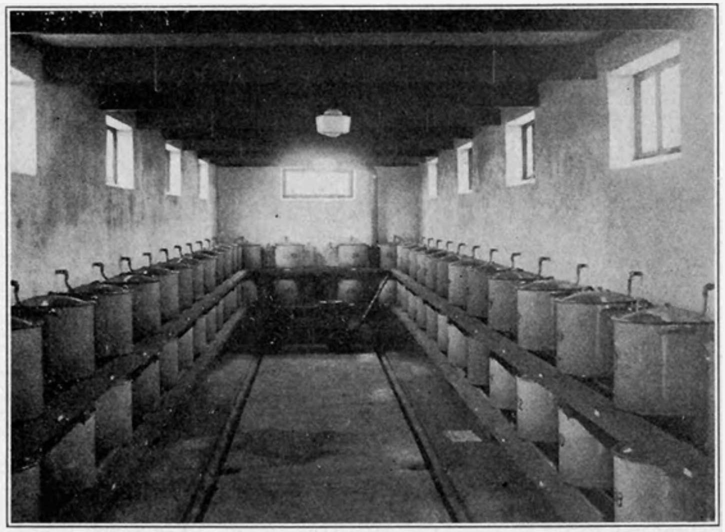

FIGURE 2. Windsor lysimeters, interior of collecting chamber, 1929.

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(A Second Report on Windsor Lysimeter Series "A")

M. F. MORGAN and O. E. STREET

THE prevailing fertilizer practices in the production of tobacco, potatoes and vegetable crops in Connecticut provide for large annual applications of nitrogen, ranging upward to 200 pounds per acre. Organic materials, such as cottonseed meal, are widely used in tobacco culture. Much nitrate of soda is used in connection with vegetable production. Sulfate of ammonia is the predominant nitrogenous constituent in factory-mixed fertilizers used for potatoes and truck crops. Urea is a concentrated source of nitrogen now receiving much attention, both as a constituent in "general purpose" types of fertilizers and as a substitute for natural organic nitrogen in tobacco culture.

A group of lysimeter tanks was installed at the Windsor Substation in 1929. These were designed to provide data on the characteristics of various nitrogenous fertilizers with respect to their removal from the soil by leaching at various seasons of the year. Series "A", reported herein, involves a comparison between nitrate of soda, sulfate of ammonia, urea and cottonseed meal. Each was applied at an annual rate of 200 pounds of nitrogen per acre to four surface soils of differing physical and chemical properties. The experiment was conducted over a five-year period ending in the spring of 1934.

Drainage waters from the above lysimeters have been weighed after each period of leaching. Nitrate nitrogen was determined concurrently. Aliquot samples were composited for detailed chemical analysis by semi-annual periods. A previous publication, Bulletin 384[2] of this Station, has presented the data with respect to the various constituents in the aggregate leachings.

The present report deals chiefly with the distribution of water and nitrate leachings from the above soils and treatments under the various weather conditions which have occurred in the different seasons during the five years of the study.

PLAN OF INVESTIGATION

INFORMATION with respect to lysimeter equipment, characteristics of the various soils and the fertilizer treatments applied to each tank, was given at length in Bulletin 384. Only those details that are essential to the presentation of the present phase of the investigation need be repeated.

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[2]Morgan, M. F. Soil changes resulting from nitrogenous fertilization: a lysimeter study. Bul. 384, June, 1936.

The lysimeter equipment is illustrated in Figures 1 and 2. The tanks of Series "A" occupy the interior row on each side of the collecting chamber. These tanks are 20 inches in diameter and 9 inches in depth, exclusive of the tapering bottom filled with quartz sand. Each tank contains only the uppermost 7-inch layer of soil, or the normal plowed zone.

The following soils were transferred from fields to lysimeters in May, 1929:

Enfield very fine sandy loam: This soil is a mellow, structureless, fine sandy loam of light brown color. It is derived from a thin mantle of post-glacial loess overlying gravel and till deposits. It is of limited occurrence, found chiefly on the rolling hills east of the broader Connecticut Valley glacial outwash terraces. This soil makes very high grade tobacco land, and also is especially well adapted to potatoes and other intensively cultivated crops. (Obtained from the tobacco field of Mr. P. J. Chamberlain, 2.5 miles southeast of Broad Brook, in East Windsor.)

Merrimac loamy sand: This soil is a porous, structureless, coarse sand of dark brown color. It is derived from a deep, stratified, coarse sand deposit comprising one of the higher glacial outwash terraces of the Connecticut Valley. Although too low in moisture holding capacity for most crops, it has been extensively planted to shade tobacco during the past 25 years. (Obtained from the shade tobacco field of Harry Griswold, one-half mile west of Bull Run crossroads, in Windsor Locks.)

Wethersfield loam: This soil is a firm, soft, granular loam, or clay loam, of red-brown color. It is developed from glacial till deposits derived chiefly from Triassic red shales. It is somewhat too heavy in texture to produce high quality cigar wrapper tobacco, and is more extensively used for grass hay, corn and late vegetable crops. (Obtained from a timothy sod field, formerly in tobacco, of Olds and Whipple, 1.5 miles south of Suffield village, in Suffield.)

Merrimac sandy loam: This soil is a dense, structureless sandy loam of medium brown color. It is derived from the deep, stratified, medium sand deposits which represent the major portion of the more extensive glacial outwash terraces of the Connecticut Valley. This soil is commonly used for tobacco of all three of the types grown in the section (Havana Seed, Broadleaf and Shade). It is also moderately well adapted to potatoes and early vegetable crops. (Obtained from the oat-cover-crop tobacco plot of the Windsor Substation, just south of the lysimeter site.)

The amounts of soil used in the tanks, on the dry weight basis, were as follows:

	Lbs. per Tank	Lbs. per Acre of total soil	Lbs. per Acre of 2 mm. soil
Enfield very fine sandy loam	80.8	1,616,000	1,604,000
Merrimac loamy sand	99.5	1,990,000	1,956,000
Wethersfield loam	90.7	1,814,000	1,580,000
Merrimac sandy loam	102.7	2,054,000	2,030,000

Pertinent physical characteristics of the above soils are given in Table 1.

TABLE 1. PHYSICAL AND CHEMICAL CHARACTERISTICS OF SOILS USED IN WINDSOR LYSIMETER SERIES "A", 1929-1934

		Enfield v. f. s. l.	Merrimac l. s.	Wethersfield l.	Merrimac s. l.
Mechanical Analyses					
Sand	%	45.4	84.0	41.4	77.0
Silt	%	41.0	10.2	32.6	15.0
Clay (.005 mm.)	%	13.6	5.8	26.0	8.0
Clay (.002 mm.)	%	11.6	4.9	19.1	6.8
Volume Weight (in place in tanks after fully settled)		1.18	1.40	1.37	1.49
Total Water-holding Capacity (oven-dry basis)	%	38.9	20.6	30.9	23.8
expressed as equivalent acre-inches for 7" depth of soil		2.75	1.77	2.15	2.11
Moisture Equivalent	%	15.7	6.1	18.6	9.6
expressed as equivalent acre-inches for 7" depth of soil		1.11	.53	1.30	.86
Organic Matter	%	3.00	1.40	2.20	1.55
Nitrogen - Total	%	.118	.045	.114	.073
Total Base Exchange Capacity (in mil-equiv. per 100 gms. soil)		6.91	3.24	7.95	5.13
Exchangeable Bases (in mil-equiv. per 100 gms. soil)		1.45	.79	4.52	2.14
Soil Reaction	pH	4.70	4.99	5.44	5.17

The fertilizer treatments were applied in dry form, mixed thoroughly with the upper 2 or 3 inches of soil, on May 26 of each year of the experiment. Each treatment was in duplicate on opposite sides of the collecting chamber.

All tanks received phosphoric acid at the rate of 100 pounds, potash at the rate of 200 pounds and magnesia at the rate of 50 pounds (30 pounds for the first two years) per acre per year. These were supplied as precipitated bone, carbonate and sulfate of potash, and carbonate of magnesia, or as constituents of the organic nitrogenous fertilizer. Each of the nitrogen treatments supplied 200 pounds of nitrogen per acre annually.

At the conclusion of each period of leaching, the quantities of water appearing in the collecting vessels were weighed and sampled. Nitrate nitrogen was determined immediately on each lot of leachate, using the phenol-di-sulfonic acid method[1]. Aliquot samples from successive periods of leaching were placed in one-gallon glass bottles containing 5 cc of toluene to prevent further biologic action. The weighted composites thus obtained were analyzed for nitrates and other constituents by six-month periods, ending on May 25 and November 25 of each year.

[1]Official and tentative methods of analysis of the Association of Official Agricultural Chemists, Second Edition, 1925.

PRECIPITATION AND OTHER WEATHER CONDITIONS DURING THE EXPERIMENT

THE time of installation of these lysimeters was practically coincident with the beginning of an unusually dry cycle. Annual rainfall was considerably below normal except for the lysimeter year ending May 25, 1933. The year by year weather conditions, as related to the occurrence of leaching, will be briefly reviewed in the following paragraphs.

1929-'30: Following a long period of dry, hot weather, a heavy storm of 2 to 3 inches on August 1 produced leaching on all tanks. Two other storms later in August gave some drainage. September was dry. October, with near normal rainfall, gave two leaching periods. November, although somewhat below normal in rainfall, was cool and the total rainfall was concentrated in two storm periods with leaching. December, with near-normal rainfall and several days of mild, rainy weather, permitted leaching. January, although below normal in rainfall, was mild, with two periods when the frost left the soil. February was above normal in temperature late in the month, with a thaw that permitted leaching. March, with two periods of heavy rains, caused much leaching. April and early May were very dry. A period of wet, humid weather during the latter half of May caused leaching and brought the rainfall above normal for the month.

1930-'31: Except for a storm period in early June, the summer and early fall were dry and hot with only one storm period sufficient to cause leaching, in mid-August. Late October and early November were wet, with occasional leaching. The winter was moderately cold and dry, with the soil frozen and blanketed with snow for much of the time. Heavy rains thawed the ground in early March, producing much leaching, with further storm periods late in the month and in early April. Most of April was dry, with long periods without any rain. The last three weeks of May were unusually wet, giving three leachings.

1931-'32: The wet period beginning in May continued until June 17, with three further leachings. Dry and hot weather then set in. Frequent light showers in July were insufficient to saturate the soil. The dry period was broken in mid-August by heavy rains causing extensive leaching. Dry weather again appeared, continuing through the fall months. The rainfall for September, October and November totaled only 3.46 inches, or more than 7 inches below normal. Frequent rains and warm weather in December gave much leaching. January was unusually wet and mild and most of the rainfall leached through the soil. February, although moderately mild, was dry, with no heavy rains; hence leaching was light. Very wet weather in late March gave exceptionally large amounts of leaching. Except for a rainy period in early April, the spring was very dry.

1932-'33: A heavy storm in mid-June caused leaching. Following several weeks of dry weather, a rain of 1.52 inches on July 27 failed to produce leaching. However, the restored moisture conditions permitted leaching after lighter rains during the next few days. Heavy rains in August gave only light leaching. Temperatures were much above normal. In September, the rainfall concentrated in two storms, with leaching. This was also true in October. November was wet during the first three weeks of the month, an accumulation of nearly 4 inches in four days giving leaching of nearly equal

amount. Late November and December were moderately dry. However, a thaw about the first of the new year caused leaching of much of the January rainfall. Light rains and snows through January, with frozen soil underneath, permitted no further leaching until a thaw at the end of the first week of February. A heavy snow followed, which was not dissipated until thawing conditions in early March. Further heavy rains during the third week of March caused much leaching. This condition was repeated in early April. The balance of the month and all of May were dry, although frequent light showers occurred.

1933-'34: June and July were moderately dry. A heavy rain of 1.28 inches on July 11 produced leaching only from the two sandier soils. In August scattered showers, culminated by heavy rains near the end of the month, gave leaching. In September two heavy storms during the first half of the month produced much leaching. Late September, October and November were very dry. The unusually cold weather of the winter of 1933-'34, attaining record low temperatures in February, 1934, prevented leaching except from a few tanks that thawed after heavy rains in early January. Heavy accumulations of snowfall were irregularly distributed over the tanks as a result of drifting conditions. Rains in March, added to melting snow, filled the 2-inch space above the frozen soil surface, resulting in considerable spillage. Heavy rains and warm weather late in March finally broke through the soil, and very heavy leaching took place. Further unusually heavy precipitation, attaining 3.08 inches on April 12, gave much additional drainage. Late April and early May were dry, with scattered showers, producing leaching in only one instance. The tanks were removed before the rainy period beginning on May 21, to be refilled for a further experiment before the beginning of the next lysimeter year.

The precipitation during the various months of the five-year period is given in Table 2. Data for a number of winter months are from the Hartford weather station, six miles southward. Otherwise, the records are from a standard rain and snow gauge set up in the vicinity of the lysimeters.

It is evident that the average precipitation was abnormally low during most of the year. Only two months, March and May, were above normal, while the months of February, July, September, October and November were especially dry. July, normally the wettest month, was the driest one during this experiment. Average precipitation during the lysimeter year was 7.83 inches below the Hartford mean for the 78 years ending in 1937. However, at least one of the years has given approximately normal rainfall for each month.

TABLE 2. DISTRIBUTION OF RAINFALL BY MONTHS—1929-1934
(IN INCHES)

	1929	1930	1931	1932	1933	1934	5-yr. Av.	Mean (Hartford) 78 yrs.
Jan.		2.51*	3.46*	4.59*	1.73	4.11	3.28	3.94
Feb.		2.05*	1.65*	2.17*	3.89	3.98*	2.75	3.83
March		3.64*	4.26*	4.89*	5.56	3.84*	4.44	3.90
April		1.54	2.46	1.53	4.13	5.35	3.00	3.36
May		4.48	6.52	1.65	1.58	3.85	3.62	3.60
June	1.67	3.72	4.74	2.86	1.96		2.99	3.08
July	.98	2.63	1.84	3.99	2.43		2.37	4.37
Aug.	4.87	2.33	3.87	5.72	3.42		4.04	4.29
Sept.	2.12	1.56	.98	3.53	4.85		2.61	3.49
Oct.	4.02*	2.36*	1.70	4.18	1.70		2.79	3.50
Nov.	2.64*	2.71*	.78	5.54	.58		2.45	3.55
Dec.	3.85*	2.35*	3.00	1.88	3.44		2.90	3.97
Total for yr. ending May 25		**33.50**	**35.63**	**32.17**	**44.72**	**39.23**	**37.05**	**44.88**

*Data from Hartford gauges, U. S. Weather Bureau.

MOISTURE RELATIONSHIPS OF SOILS USED IN LYSIMETER SERIES "A"

DURING the summers of 1929 and 1930 seven-inch depths of the various soils used in the lysimeters were kept in 10-inch glazed earthenware jars, with outlet hole at the bottom, imbedded in the courts adjacent to the lysimeter tanks. Moisture contents were determined at weekly intervals throughout the season. This provided excellent data as to the amount of water retained by the soils at various periods after rainfalls producing leaching; in other words, after the soils had been saturated. These results were supplemented by greenhouse studies of a similar nature.

From the above data, a graph has been plotted indicating the moisture contents of the soils at various intervals of time without rain subsequent to soil saturation. This is presented in Figure 3.

The Enfield very fine sandy loam, as a consequence of its high porosity and unusually uniform "size of particle" distribution (over 60 percent of the material between .05 and .10 mm.) has the highest water holding capacity at the point of saturation. Also, as a consequence of its porosity and excellent capillary structure, it evaporates water readily. In four weeks the moisture content fell from 38.9 percent to 9.8 percent.

The Wethersfield loam, while considerably more colloidal than the Enfield, is much more compact. It has a definite crumb structure, the interstices of coarser soil within the crumbs being largely filled with finer material. As a result, this soil has a somewhat lower total water holding capacity. However, it loses water by evaporation less rapidly and, during the later stages of drying, gives up moisture from the interior of the granular particles at a greatly reduced rate. Hence in four weeks it declined in moisture content from 33.03 percent to 10.1 percent, the latter figure slightly greater than for the Enfield soil at the same time.

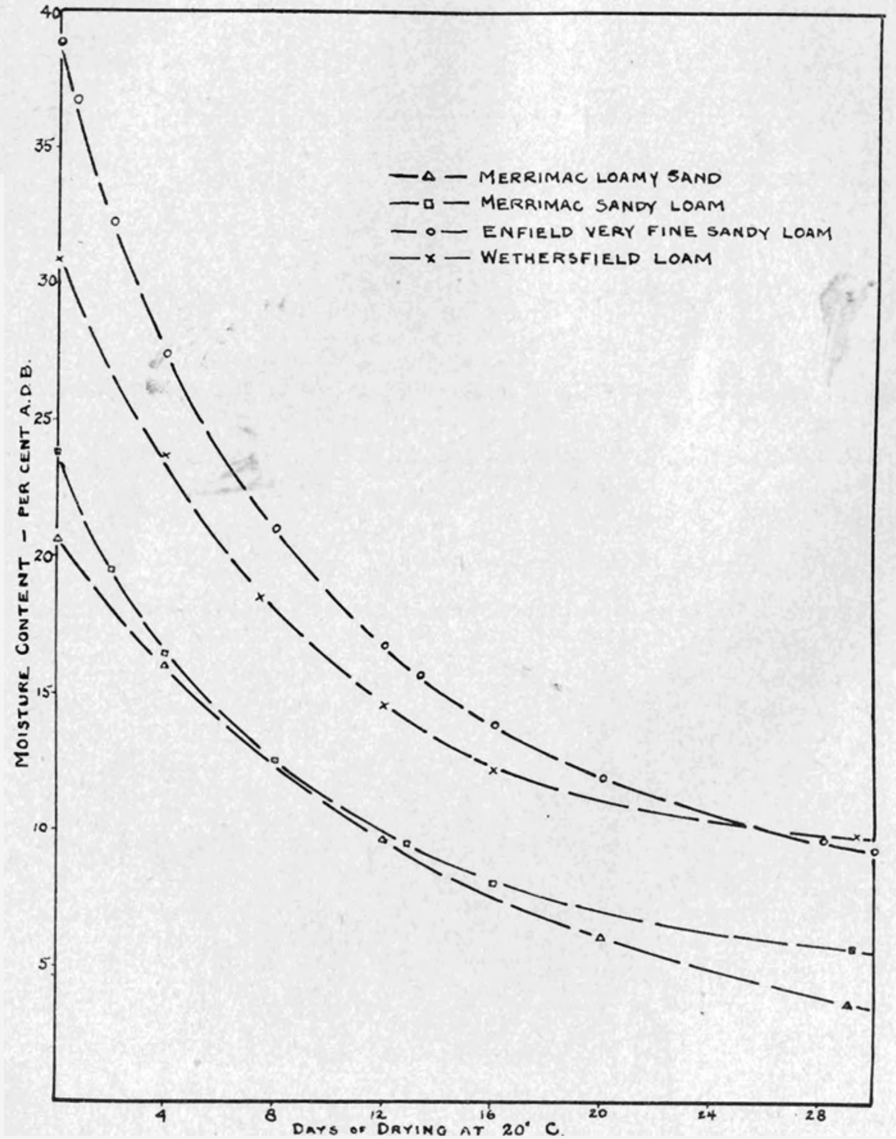

FIGURE 3. Moisture content of surface soils used in Lysimeter Experiment A, after varying intervals of drying.

The Merrimac sandy loam soil has an unusually high volume weight, 1.49, as a consequence of the well proportioned distribution of particles of all sizes. In the earlier stages of drying, it provides excellent capillarity, with little tendency toward self-mulching due to a film of dry earth on the soil surface. The initial water loss is thus rapid. After a few days the mulching begins to be effective. Movement of air through the restricted internal pores is slow; hence there is a definite retardation of water loss in the later stages.

The Merrimac loamy sand contains a larger amount of coarse sand, and the amount of fine material is not sufficient to occupy as much of the space between the coarser grains as in the loamier Merrimac. Its capillarity is less perfect. Within a very short time it forms a loose sandy coating of dry soil on the surface, resulting in partial mulching against direct evaporation at the soil surface. However, air continues to circulate fairly freely through the coarse internal pores, and water loss is at an only slightly diminishing rate. Thus, while at the end of one week the moisture contents of the two soils were practically identical, at the end of four weeks the sandier Merrimac was considerably drier.

It is of interest to observe that extrapolation of these graphs to 32 days gives values almost identical to the wilting coefficients of the soils (calculated at .6 times moisture equivalent), as follows.

Enfield v. f. s. l.	9.33	Merrimac sandy loam	5.80
Wethersfield loam	9.82	Merrimac loamy sand	3.70

It is to be noted that the above discussion applies to data on the basis of percentages by weight.

A somewhat different picture, and a more applicable one from the standpoint of water losses by leaching, is obtained by computation to moisture content of the soil in terms of inches of water per acre of actual soil used in the tanks.

Figure 4 graphically portrays the progressive water deficit of the soil in terms of inches of water per acre, during the drying period. This has been extended only to 20 days, since periods of longer duration without some rainfall are unusual.

These curves bring out the fact that the Enfield soil accumulates a water deficit at by far the greatest rate. The Wethersfield loam and Merrimac sandy loam soils, markedly different in moisture content on a unit weight basis, are almost identical in actual rate of water loss to the atmosphere. The sandier soil accumulates a slightly greater deficit in the earlier stages of drying, while later, the Wethersfield soil gives up slightly more water to the air.

The Merrimac loamy sand accumulates a moisture deficit at a definitely slower rate than the other three soils, as would be expected on the basis of its low total water holding capacity (in terms of equivalent inches of water per acre) and greater tendency toward self-mulching.

The amount of water leached through the soil is less than the amount of rainfall by an amount equal to the deficit of the soil below its total water retentiveness. For instance, after 10 days of dry weather, Soil I has lost 1.4 inches of water per acre by evaporation. Soil II has lost 0.7 inches in the

same time. A rainfall of 2.0 inches should thus produce 0.6 inches of leaching on Soil I and 1.3 inches on Soil II.

Just such a condition was revealed by the leaching on August 12, 1929. A heavy rain on August 4 had leached all soils, leaving them in a saturated condition. After nine days of dry weather with only a trace of precipitation, 1.36 inches fell in a few hours. Leaching and retention by the various soils were as follows, as an average of all tanks:

	Leached	Retained
Enfield v. f. s. l.	.04″	1.32″
Wethersfield loam	.18″	1.18″
Merrimac sandy loam	.26″	1.10″
Merrimac loamy sand	.37″	.99″

Comparison of these figures with 9-day values in Figure 4 gives reasonable agreement.

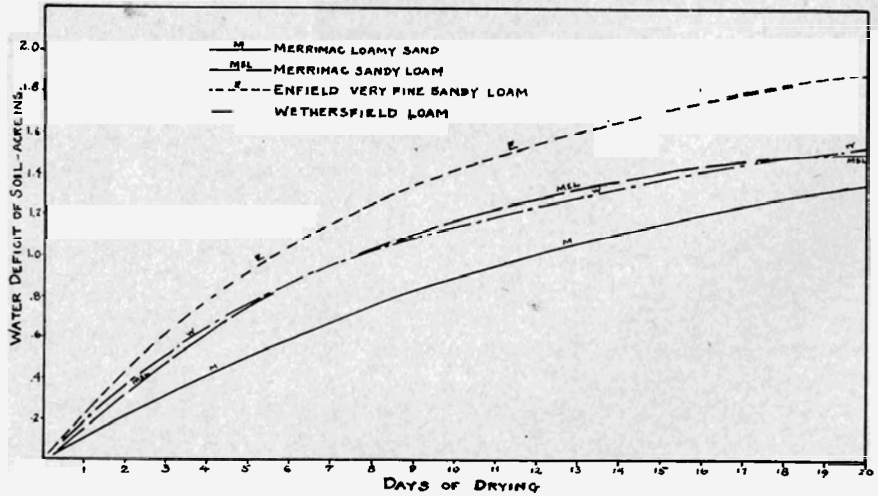

FIGURE 4. Progressive water deficit of soils used in Lysimeter Series "A", under average summer evaporation conditions.

A similar result was obtained by the rainfall of September 17, 1932, after 10 days with no rain since the previous leaching period. Of 2.10 inches of rainfall, the following amounts were leached and retained:

	Leached	Retained
Enfield v. f. s. l.	.84″	1.26″
Wethersfield loam	1.09″	1.01″
Merrimac sandy loam	1.21″	0.99″
Merrimac loamy sand	1.38″	0.72″

Under actual conditions in the lysimeters as well as in the field, the rate of evaporation varies greatly from day to day as well as from season to season. Intermittent light showers on dry soil raise the moisture content of the soil only slightly; hence the rate of evaporation is not appreciably accelerated. Humidity, temperature and air movement are all variable factors. Soil nearly saturated with water loses water at a greater rate. Thus, during the seasons of the year when the soil is maintained in a more moist condition, as in late fall, winter and early spring, the rate of evaporation is proportionately greater than would otherwise be the case at the lower temperatures.

For the purposes of comparison, the lysimeter year beginning May 26 (the date of application of fertilizer treatment) has been divided into four periods. The first, or summer period, is extended to include the last leaching rain in August. The second, or autumn period, ends on November 25, the date of collection of leachates for composite analyses*. The third, or winter period, is extended to include the final "spring thaw" leaching, near the first of April. The fourth, or spring period, ends on May 25, except for 1934, when the soils were removed by May 20 to permit refilling for a further experiment.

Data on leaching in relation to rainfall are given in Table 3.

These results show considerable differences in the proportion of rainfall leached from the various soils, for the various seasons, and for the same season in different years. Most of these differences may be explained in the light of the previous summary of the distribution of rainfall from year to year.

*Bul. 420, of this Station.

Table 3. Average Leaching by Periods—1929-34

Windsor Lysimeters—Series A

	Precipitation	Average Leaching—in Inches per Acre			
		Enfield v.f.s.l.	Merrimac l.s.	Wethersfield l.	Merrimac sdy. l.
1929-30					
May 26-Aug. 12	7.38	.56	2.26	.95	1.52
Aug. 13-Nov. 25	8.67	2.36	3.63	2.90	3.15
Nov. 26-Mar. 26	11.92	5.69	7.10	6.22	5.86
Mar. 27-May 25	5.53	.11	.63	.45	.56
Total for year	**33.50**	**8.72**	**13.62**	**10.52**	**11.09**
1930-31					
May 26-Aug. 16	9.00	1.25	2.33	1.87	2.01
Aug. 17-Nov. 25	7.04	2.07	2.94	2.54	2.64
Nov. 26-Apr. 2	12.72	5.17	4.20	4.87	4.46
Apr. 3-May 25	6.87	2.31	2.93	2.78	2.86
Total for year	**35.63**	**10.80**	**12.40**	**12.06**	**11.97**
1931-32					
May 26-Aug. 15	11.46	3.79	5.27	4.45	4.74
Aug. 16-Nov. 25	3.57	—	.02	—	—
Nov. 26-Mar. 29	14.34	8.83	10.92	10.00	10.08
Mar. 30-May 25	2.80	1.04	1.29	1.07	1.12
Total for year	**32.17**	**13.66**	**17.50**	**15.52**	**15.94**
1932-33					
May 26-Aug. 24	11.34	.55	2.16	1.44	1.54
Aug. 25-Nov. 25	15.24	8.02	9.62	8.93	8.92
Nov. 26-Mar. 23	12.48	9.27	10.79	11.65	11.28
Mar. 24-May 25	5.66	3.31	3.48	3.58	3.43
Total for year	**44.72**	**21.15**	**26.05**	**25.60**	**25.17**
1933-34					
May 26-Aug. 25	8.23	.53	1.22	.81	.93
Aug. 26-Nov. 25	7.34	2.38	3.08	2.68	2.86
Nov. 26-Apr. 2	15.59	3.45	4.67	3.44	3.29
Apr. 3-May 20*	7.34	3.44	3.71	3.41	3.50
Total for year	**38.50**	**9.80**	**12.68**	**10.34**	**10.58**
(*Soil in tanks removed)					
Average—1929-34					
Summer—85 da.	9.48	1.34	2.65	1.90	2.15
Fall—99 da.	8.37	2.97	3.86	3.41	3.51
Winter—124 da.	13.41	6.48	7.54	7.24	6.99
Spring—56 da.	5.64	2.04	2.41	2.26	2.30
Total for year	**36.90**	**12.83**	**16.46**	**14.81**	**14.95**

Table 4 summarizes the average seasonal and daily evaporation from the various soils during the five years of the experiment, and the percentage of total precipitation leached and lost by evaporation.

TABLE 4. RATE OF EVAPORATION AT VARIOUS SEASONS
Windsor Lysimeters—Series A

	Inches per Acre—Average Data 1929-34			
	Enfield v.f.s.l.	Merrimac l.s.	Wethersfield l.	Merrimac sdy. l.
EVAPORATION (inches of rainfall)				
Summer—85 days	8.14	6.83	7.58	7.33
per day	.096	.080	.089	.086
Fall—99 days	5.40	4.51	4.96	4.86
per day	.055	.046	.050	.049
Winter—124 days	6.93	5.87	6.17	6.42
per day	.056	.047	.050	.052
Spring—56 days	3.60	3.23	3.38	3.34
per day	.064	.058	.060	.060
Entire year	24.07	20.44	22.09	21.95
per day	.066	.056	.061	.060
RELATIVE PERCENTAGES EVAPORATED AND LEACHED				
Summer				
Evaporated	85.87	72.05	79.96	77.32
Leached	14.13	27.95	20.04	22.68
Fall				
Evaporated	64.52	53.88	59.26	58.06
Leached	35.48	46.12	40.74	41.94
Winter				
Evaporated	51.68	43.77	46.29	47.87
Leached	48.32	56.23	53.71	52.13
Spring				
Evaporated	64.46	57.27	59.96	59.22
Leached	35.54	42.73	40.07	40.78
Entire year				
Evaporated	65.23	55.39	59.86	59.49
Leached	34.77	44.61	40.14	40.51

There have been no consistent differences in quantity of leaching from the same soils under various treatments, except in the case of cottonseed meal, which has regularly given more leachate for each of the soils during practically every summer period of leaching. In a number of instances cottonseed meal permitted slight leaching when the precipitation was insufficient to satisfy the moisture deficit in all other cases.

The following table gives the increased leaching due to cottonseed meal for the summer period:

TABLE 5. INCREASED WATER RETENTIVENESS OF SOIL AGAINST EVAPORATION LOSS DURING THE SUMMER SEASON. AVERAGES—1929-34.
Windsor Lysimeters—Series A

	Decreased evaporation inches per acre Summer period 85 days	per day	Moisture conservation lbs. water per acre during summer period
Enfield v. f. s. l.	.180	.0021	40,837
Merrimac l. s.	.554	.0065	125,687
Wethersfield l.	.368	.0043	83,490
Merrimac sdy. l.	.228	.0027	51,728

Under the conditions of this experiment the surplus water retained against evaporation was lost by leaching. However, it is reasonable to suppose that under crop this would supply additional water for plant growth. On the Merrimac loamy sand soil, the increased water content of the soil resulting from the use of cottonseed meal is sufficient for the moisture needs of about 125 pounds of tobacco (assuming 1000 pounds of water for one pound of dry weight in crop).

The effects of cottonseed meal were not conspicuous at other seasons; at higher average moisture contents, the benefits from this organic material in the soil would be largely masked. It is also to be considered that most of the cottonseed meal would be lost by decomposition within a few months after application.

RATE OF LEACHING OF NITRATE NITROGEN FROM VARIOUS SOILS

THE nitrate of soda treatment used in this experiment affords an excellent measure of the rate of leaching of nitrate nitrogen from the soil. Two hundred pounds of nitrate nitrogen per acre, applied annually on May 26, was completely removed from all soils in the course of each year, together with small additional amounts of nitrates liberated by biological processes. However, the latter was insignificant in proportion to the former.

PROGRESSIVE NITRATE NITROGEN CONCENTRATIONS OF THE LEACHINGS FROM NITRATE OF SODA TREATMENTS

THE fertilizer materials were incorporated in the upper 2 or 3 inches of the soil; hence the first increments of leaching contained little nitrate nitrogen. The concentration of the leachate, in terms of parts per million determined on successive increments of leaching during the year, affords one measure of the rate of nitrate exhaustion.

These data were plotted with reference to the cumulative acre inches of leachate after the application of the nitrate of soda. Figure 5 shows a typical distribution curve on this basis. The curve fitting represents the apparent mean trend with progressive leaching. It must be pointed out that there was much variation in the time factor. In some years little leaching took place until late fall, while in others a considerable early summer leaching was followed by a long period without leaching. This would tend to vary the concentrations in proportion to the progressive movement of water downward through the soil, since in dry periods there is presumably some concentration of nitrates toward the surface. It must

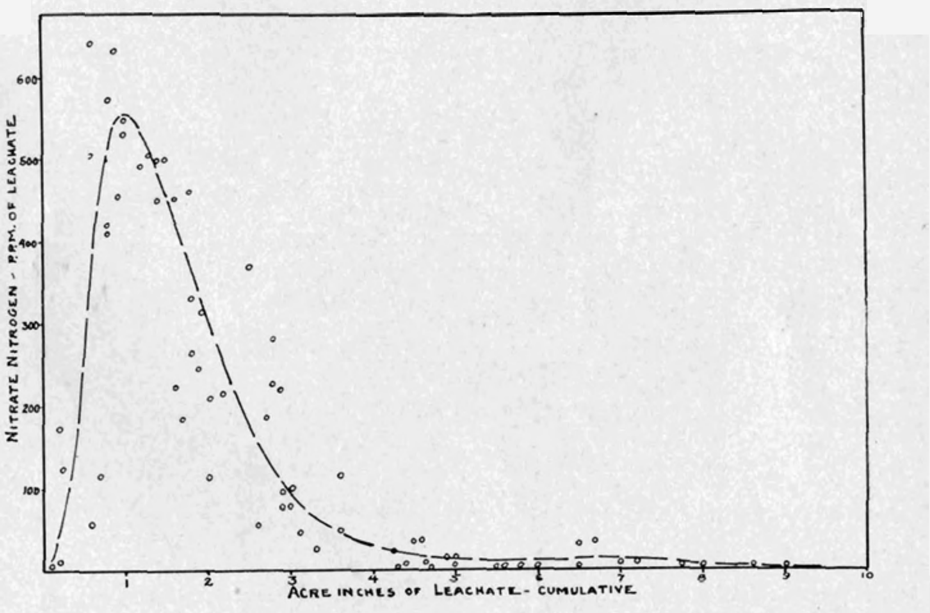

FIGURE 5. Distribution curve showing concentration of nitrate nitrogen in the water leached from nitrate of soda treatment, Merrimac sandy loam soil, in relation to the cumulative volume of leaching since the fertilizer was applied.

also be considered that the concentration measurements represent the mean of each separate collection of leaching, varying from a few hundredths of an inch to 4 inches or more.

Figure 6 shows the fitted curves for the four soils.

In general, these results are in harmony with the characteristics of the various soils, as presented earlier in this publication. The sandiest soil, Merrimac loamy sand, attained the earliest maximum of concentration, followed by a rapid decrease. The somewhat less sandy Merrimac sandy loam required a slightly greater quantity of leaching to attain a peak, and held up the leaching concentration longer. The apparent lag of the former soil, as compared to the latter, beyond three inches may indicate some delay in biological nitrate formation within the more sandy soil toward the fall period when moisture conditions became more generally favorable.

Both the Wethersfield loam and the Enfield very fine sandy loam soils required more leaching to attain a maximum concentration, and maintained a considerable nitrate level until more than five inches of leaching had occurred. It is to be noted that the former soil gave a somewhat earlier maximum than the latter, although it held back a significant amount of nitrates until all the other soils were practically exhausted. Two possible factors may be here involved. The Wethersfield loam soil retains a definite crumb structure. The nitrate nitrogen may be leached from the exterior of the crumbs more rapidly than from the crumb "cores". It is also possible that there is a delay in biologic nitrate liberation within the crumbs.

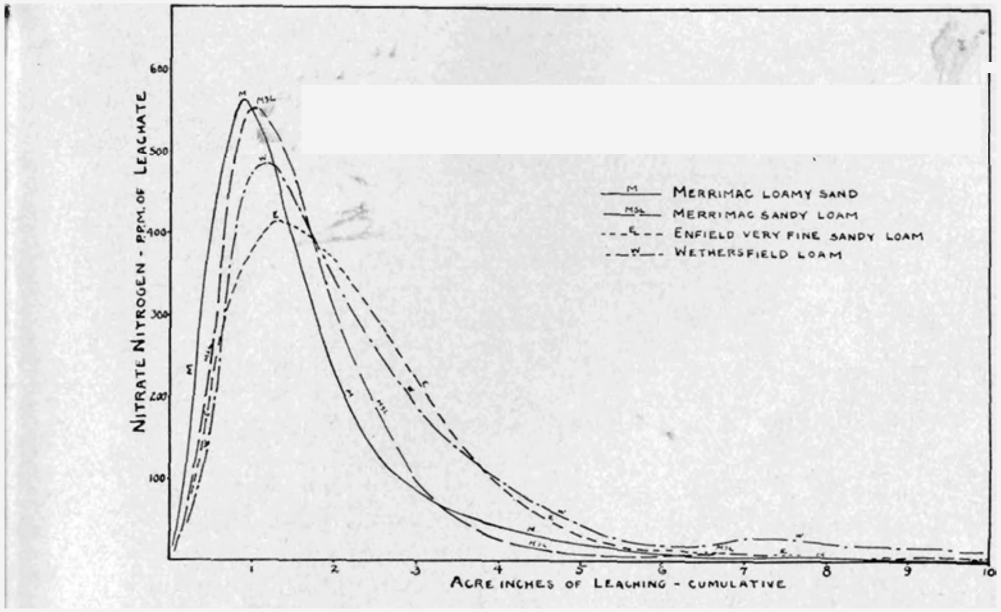

FIGURE 6. Relationship between concentration of nitrogen in the water leached and the cumulative volume of leaching since the nitrate of soda treatment.

RATE OF NITRATE NITROGEN LEACHING IN RELATION TO TOTAL YEARLY QUANTITIES LEACHED

As has been shown in the preceding paragraphs, the concentrations of nitrates in the leachings under the nitrate of soda treatments diminished progressively as more and more water passed through the soil, except for the initial lag required to attain a maximum and for the slight pick-up in concentration exhibited by the Wethersfield soil. Calculations of actual quantities of nitrate nitrogen leached by successive increments of leaching have made it possible to show the rate of removal of nitrate nitrogen by leaching in relationship to the total amount originally present in the soil.

The data for cumulative quantities of nitrate nitrogen per acre, later summarized in Table 8, have been computed in terms of percentages of total yearly nitrate nitrogen removals by leaching. No great error is introduced by assuming that in case of nitrate of soda all of this amount was present in the soil at the beginning of the lysimeter year, on May 26, since the total yearly leaching only slightly exceeded the initial application, from all the soils.

The most reasonable concept of nitrate leaching under such conditions is that each successive increment of leaching will remove nitrates in a definite proportion of the amount left in the soil. This is mathematically expressed by the formula:

$$\frac{dx}{dt} = K (A - x)$$

Here "dx" is the infinitely small increase in the total quantity of nitrate nitrogen leached by an infinitely small increment of water leaching "dt"; "A" is the total quantity of nitrogen initially present in the soil, and "K" is constant, determined by the characteristics of the soil with respect to susceptibility to leaching. This is analogous to chemical reactions of the first order, plant growth curves in relation to various growth factors and many other phenomena of the same type.

In order that such relationships may be more simply expressed, Baule* has introduced the term "Baule unit" to express the amount of a given factor which will account for 50 percent of the total quantity involved. If this is applied to the phenomenon of nitrate leaching, the first Baule unit of leaching will remove one-half of the nitrates; the second will remove one-half of the remaining 50 percent, or 25 percent; the third will remove one-half of the remaining 25 percent, or 12.5 percent, and so on. The cumulative totals of nitrate leaching would thus be as follows:

1 Baule unit........	50.00%	4 Baule units.......	93.75%
2 Baule units.......	75.00%	5 Baule units.......	96.83%
3 Baule units.......	87.50%	10 Baule units.......	99.99%

Except for the initial lag following nitrate nitrogen application in the uppermost layers of the soil, during which no significant nitrate leaching occurs, the data appeared to fit the foregoing concept to a remarkable degree. The results for the two more leachy soils (Merrimac loamy sand and sandy loam) are plotted in the lower section, and for the two less leachy soils (Wethersfield loam and Enfield fine sandy loam) in the upper section, respectively, of Figure 7. The smoothed curves are based on calculated Baule units of leaching as follows:

Merrimac loamy sand.........	0.9 acre inches of leaching
Merrimac sandy loam.........	1.0 acre inches of leaching
Enfield v. f. s. l..............	1.2 acre inches of leaching
Wethersfield loam............	1.6 acre inches of leaching

The two more sandy soils are apparently very similar in their ratios of washing of nitrates from the soil as affected by actual quantity of drainage water passing through them. The Enfield soil shows somewhat greater initial lag, but is actually less retentive of nitrates when subject to the same *quantity* of leaching.

*Baule, B., Landw. Jahrb. 51:363, 1918.

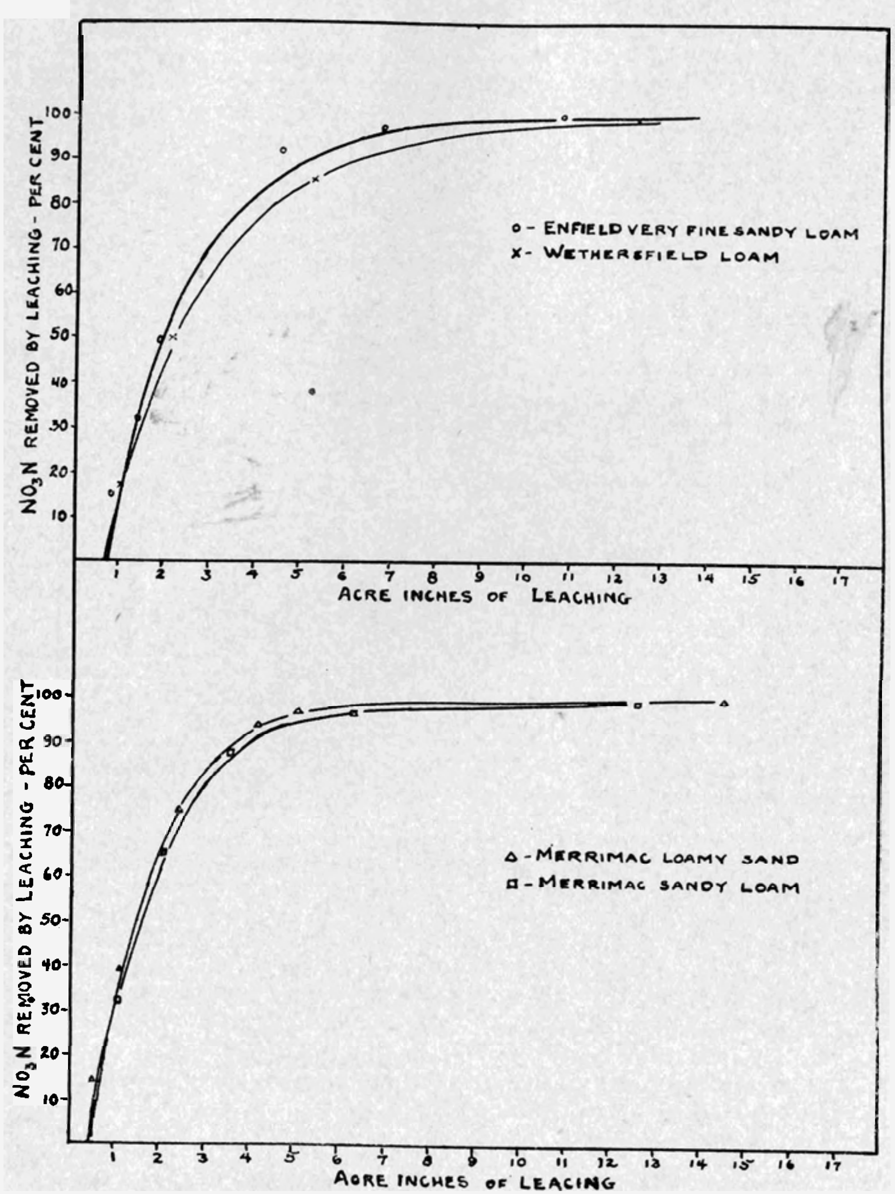

FIGURE 7. Progressive removal of nitrate nitrogen from surface soil by leaching, from various soils used in Lysimeter Series "A", nitrate of soda treatment.

When the nitrates are initially well distributed through the entire soil, or attain a given concentration in the soil through biological processes, the lag in leaching from the surface soil into the outlet tubes, as in case of these lysimeters, or into the subsoil, as in natural soil conditions, would not be involved. For purposes of simplification, calculated average rates of nitrate leachings for the two more leachy soils and for the two less leachy soils are shown in Figure 8. From this graph one may estimate the proportionate amounts of nitrate loss from the surface soil produced by various quantities of drainage water, on both sandy and loamy soils of the Connecticut tobacco area.

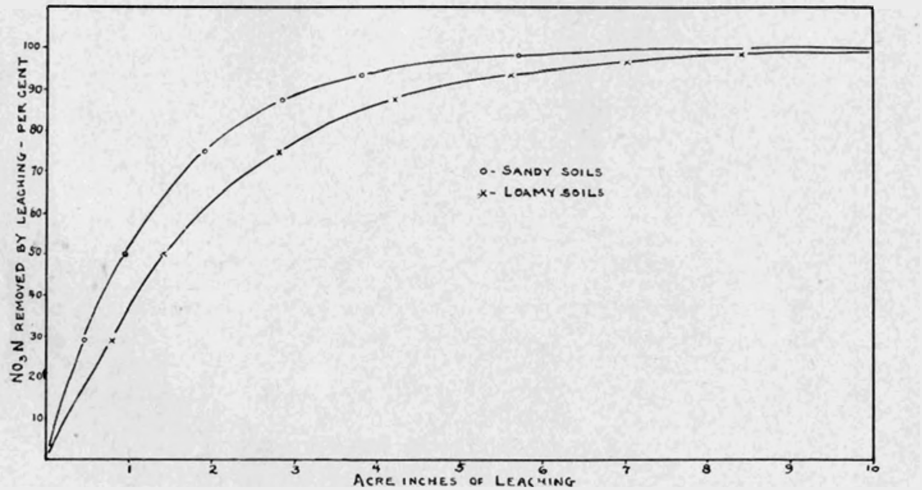

FIGURE 8. Average progressive removal of nitrate nitrogen from two loamy and two sandy soils following nitrate of soda treatment, in relation to volume of leaching.

SEASONAL FACTORS AFFECTING RATES OF NITRATE LEACHING UNDER VARIOUS SOIL CONDITIONS

THE preceding picture of nitrate leaching shows the rate of nitrate leaching to be expected from a given quantity of water passing through the soil. It has also been shown how soils acquire moisture deficits during intervals between rainy periods, and that these deficits vary with the character of the soil. The amount of water draining through the soil depends upon both the amount and distribution of precipitation in relation to evaporation (as well as transpiration in case of cropped soils). Such conditions vary from year to year, and as has been pointed out, the period of 1929-34 was not a fully representative sample of average weather conditions. However, the data collected during these years have given at least a good qualitative measurement of the rate of nitrate leaching on various soils under the operation of varying weather conditions from season to season.

Figure 9 graphically expresses the progressive leaching of nitrates from the various soils, by months, in relation to rainfall, based on averages for the five years.

With the exception of the abnormally low average July rainfall, producing little or no leaching, the outgo of nitrates in the soil progressed rather regularly from month to month. It is to be noted that the Enfield soil, inherently more leachy than the Wethersfield, lost nitrates much less rapidly during the summer months. This was due to the greater moisture deficit resulting in this soil from warm, dry periods, with consequent lessened volume of leaching. After the drying of the soil became less, during fall and winter months, the Enfield manifested its natural characteristics with respect to leachiness. On the other hand, since the Wethersfield and Merrimac sandy loam soils attain similar moisture deficits in dry periods, the consistent differences in their rates of leaching were in accord with their natural nitrate retentiveness. The differences between the Merrimac

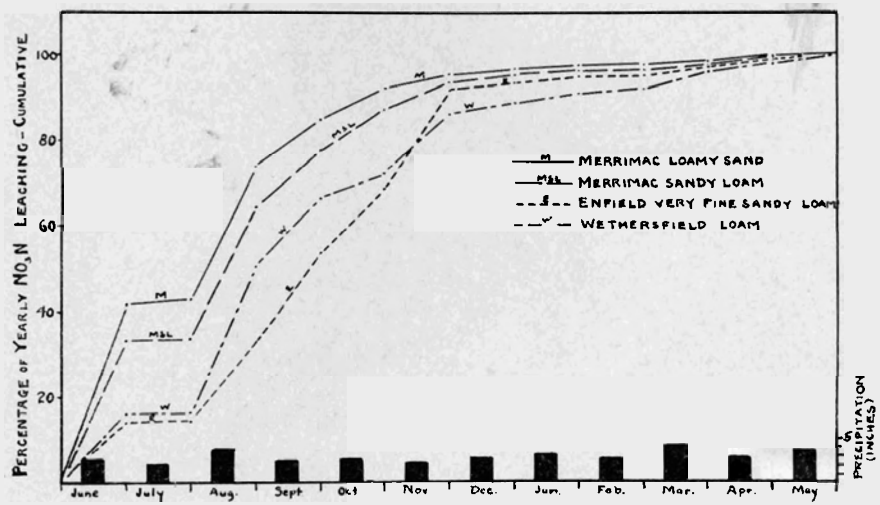

FIGURE 9. Progressive leaching of nitrate nitrogen from soils used in Lysimeter Series "A", by months, in relation to rainfall. (Average data 1929-34) Nitrate of soda treatment.

sandy loam and Merrimac loamy sand were probably more largely due to the more rapid evaporation of water from the former soil, than to its slightly greater ability to hold nitrates.

APPROXIMATE ESTIMATION OF THE DEGREE OF NITRATE LEACHING

THE above studies may be used as a working basis for estimating the approximate extent of nitrate leaching from rainy periods during the growing season. For practical purposes, the soils of the Connecticut Valley section may be roughly divided into two classes, sandy soils and loam soils. The former includes loamy sand and sandy loam textural classes, while the latter comprises the fine and very fine sandy loams, loams and silt loams. The data with respect to water deficits (Figure 4) and proportionate nitrate leaching from given increments of drainage water (Figure 8) provide a means of estimating the degree of nitrate depletion to be expected from determined amounts of rainfall occurring during the storm period.

Figures 10 and 11 show the percentages of nitrates that may be expected to wash into the subsoil to a depth of more than 8 inches, when two-, ten-

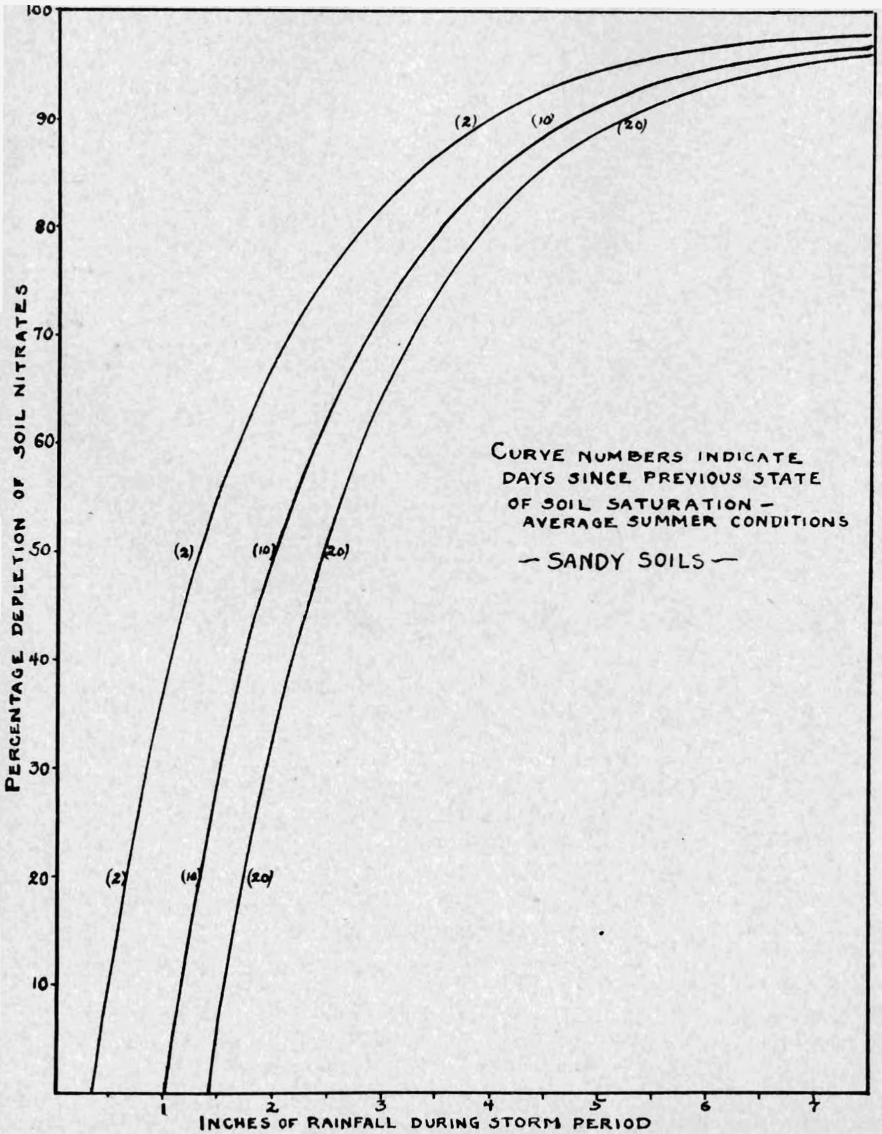

Figure 10. Depletion of nitrate nitrogen from sandy soils in relation to amount of rainfall during the storm period and the previous interval of dry weather, under average summer conditions.

and twenty-day intervals of reasonably dry weather have passed since the last storm period giving rainfall sufficient to saturate the soil.

Such estimations apply only to conditions where all of the surplus rainfall leaches through the soil, without run-off. This is substantially true of the level areas of sandy soils most used for tobacco in the Connecticut Valley. With a part of the precipitation lost by run-off, a smaller proportion of the nitrates would be leached.

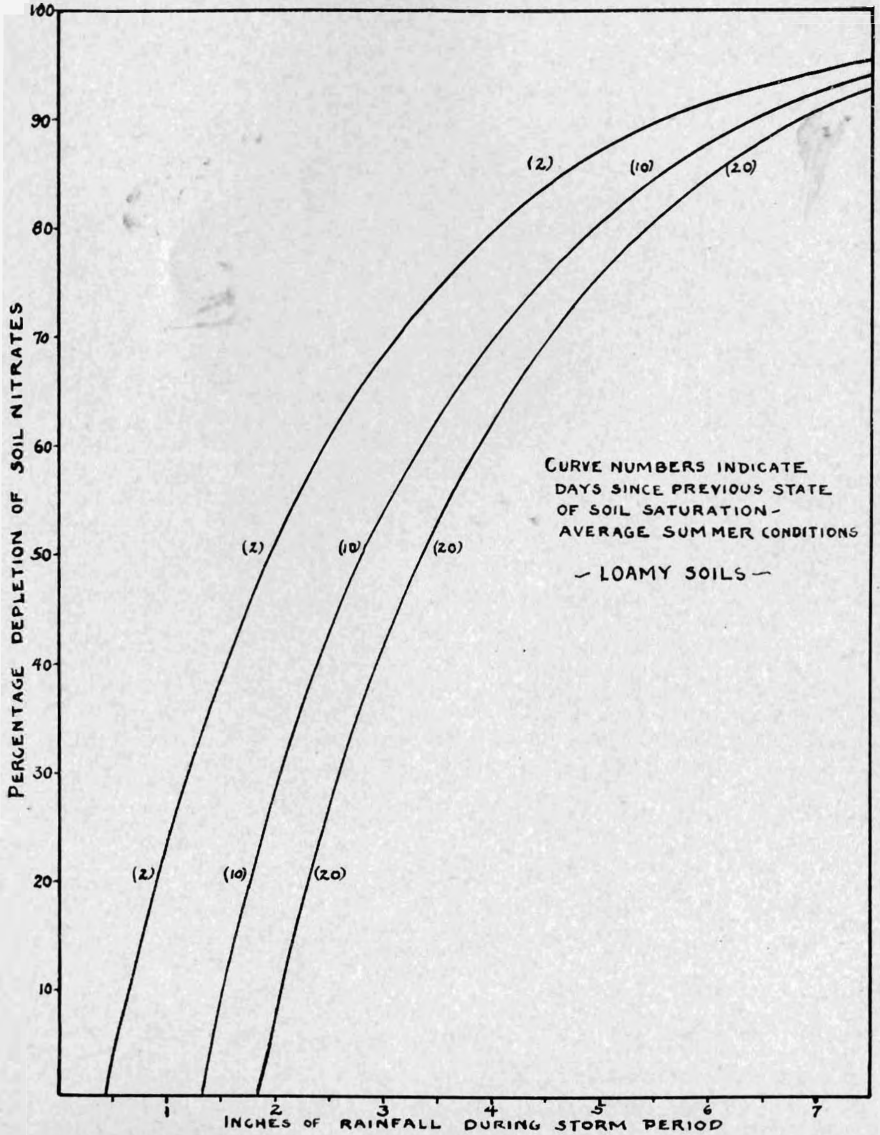

Figure 11. Depletion of nitrate nitrogen from loamy soils in relation to amount of rainfall during the storm period and the previous interval of dry weather, under average summer conditions.

NITRIFICATION AND LEACHING OF NITRATES FROM VARIOUS TYPES OF NITROGENOUS FERTILIZERS

The series of lysimeters under consideration provided comparisons between the leaching of nitrates from four sources of nitrogen, for each of the four soils, as follows: nitrate of soda, sulfate of ammonia, urea and cottonseed meal. In all cases, the yearly rate of application was 200 pounds of nitrogen on May 26. The data for individual years are presented in Tables 6 and 7.

TABLE 6. NITRATE NITROGEN LEACHING BY SEASONS

Windsor Lysimeters—Series "A", 1929-34

(in pounds per acre)

	Enfield v.f.s.l.				Merrimac l.s.			
	NS	SA	U	CM	NS	SA	U	CM
1929-30								
Summer	44.7	15.0	19.5	16.3	127.2	50.4	78.8	63.9
Fall	147.8	131.6	123.2	91.7	81.0	67.6	69.8	64.1
Winter	13.5	24.3	15.8	20.0	4.8	4.1	4.7	4.4
Spring	0.7	0.5	0.5	0.6	1.9	1.9	1.3	2.2
Year	**206.7**	**171.4**	**159.0**	**128.6**	**214.9**	**124.0**	**154.6**	**134.6**
1930-31								
Summer	40.7	17.1	14.0	7.5	189.5	26.8	48.7	22.5
Fall	170.0	147.2	139.3	86.1	29.1	46.1	41.8	57.8
Winter	9.8	35.3	29.9	21.3	3.2	2.2	3.1	3.9
Spring	3.7	8.3	8.0	8.0	2.0	1.9	2.2	2.8
Year	**224.2**	**207.9**	**191.2**	**122.9**	**223.8**	**77.0**	**95.8**	**87.0**
1931-32								
Summer	173.1	86.5	104.4	75.7	192.7	65.7	106.5	81.9
Fall	-	-	-	-	-	-	-	0.2
Winter	29.5	64.4	66.4	77.0	7.6	12.0	11.4	34.7
Spring	0.8	2.8	4.2	4.1	3.8	1.8	0.5	0.6
Year	**203.4**	**153.7**	**175.0**	**156.8**	**204.1**	**79.5**	**118.4**	**117.4**
1932-33								
Summer	56.8	9.8	11.6	7.3	160.6	70.2	127.8	47.0
Fall	155.2	155.6	166.2	108.8	42.7	56.5	45.4	45.2
Winter	3.4	2.7	3.7	3.8	2.4	1.9	2.8	3.9
Spring	2.0	1.1	1.1	1.8	0.9	0.7	1.4	1.4
Year	**217.4**	**169.2**	**182.6**	**121.7**	**206.6**	**129.3**	**177.4**	**97.5**
1933-34								
Summer	24.7	8.5	8.8	11.9	124.8	34.6	98.7	57.1
Fall	162.5	43.8	68.1	46.8	85.7	30.0	44.2	33.9
Winter	15.7	61.4	67.1	28.3	8.2	5.9	3.9	4.2
Spring	1.9	4.8	4.5	4.9	1.0	2.6	0.6	1.3
Year	**204.8**	**118.5**	**148.5**	**91.9**	**219.7**	**73.1**	**147.4**	**96.5**

The data in Tables 6 and 7 have been averaged for the five years, and are shown in Table 8. It is to be noted that this also gives separate results for the May 26—June 30 and the July 1—August 20 periods, grouped together in Tables 6 and 7, in order to simplify their presentation.

TABLE 7. NITRATE NITROGEN LEACHING BY SEASONS

Windsor Lysimeters—Series "A", 1929-34

(in pounds per acre)

	Wethersfield loam				Merrimac sdy. l.				
	NS	SA	U	CM	NS	SA	U	CM	NoN
1929-30									
Summer	78.2	33.7	47.0	41.9	138.7	83.3	101.3	78.4	27.4
Fall	89.0	124.7	113.5	57.8	111.6	117.9	118.4	96.2	49.0
Winter	53.8	30.4	49.4	33.9	7.0	6.8	6.0	6.7	7.1
Spring	2.1	1.2	1.2	1.5	5.1	4.6	4.4	5.7	4.6
Year	**223.1**	**190.0**	**211.1**	**135.1**	**262.4**	**212.6**	**230.1**	**187.0**	**88.1**
1930-31									
Summer	110.0	21.3	64.1	14.9	155.8	41.3	59.2	18.5	14.8
Fall	110.4	132.0	125.5	76.8	78.1	131.0	110.0	100.6	44.0
Winter	17.0	28.4	22.1	15.3	5.7	4.1	5.7	7.7	6.7
Spring	6.3	24.0	6.2	7.4	6.9	5.1	3.9	8.0	8.9
Year	**243.7**	**205.7**	**217.9**	**114.4**	**246.5**	**181.5**	**178.8**	**134.8**	**74.4**
1931-32									
Summer	169.5	98.2	124.4	92.7	201.9	100.9	118.7	102.8	34.6
Fall	-	-	-	-	-	-	-	-	-
Winter	41.4	78.5	47.6	52.6	23.8	27.5	23.7	47.2	25.9
Spring	0.9	0.8	0.4	0.6	0.7	1.0	0.7	1.1	0.8
Year	**211.8**	**177.5**	**172.4**	**145.9**	**226.4**	**129.4**	**143.1**	**151.1**	**61.3**
1932-33									
Summer	112.8	22.5	67.4	26.3	171.5	86.3	108.8	37.2	18.7
Fall	89.4	146.6	113.9	87.5	44.2	86.1	72.3	77.0	20.4
Winter	4.3	6.9	5.2	5.6	2.7	1.2	4.4	6.2	5.6
Spring	1.2	1.8	1.1	1.5	0.7	0.3	1.6	1.8	1.5
Year	**207.7**	**177.8**	**187.6**	**120.9**	**219.1**	**173.9**	**187.1**	**122.2**	**46.2**
1933-34									
Summer	67.0	15.9	39.7	47.1	91.5	39.7	64.1	60.4	10.6
Fall	121.1	51.7	123.2	91.0	109.6	43.8	88.4	58.3	11.2
Winter	24.5	57.1	25.4	8.9	4.6	25.6	9.0	6.4	4.8
Spring	3.5	7.3	3.3	2.8	4.0	5.9	2.8	2.4	1.5
Year	**216.1**	**132.0**	**191.6**	**149.8**	**209.7**	**115.0**	**164.3**	**127.5**	**28.1**

TABLE 8. CUMULATIVE LEACHING OF NITRATE NITROGEN BY PERIODS.
AVERAGE DATA—1929-34
Windsor Lysimeters—Series "A"
(in pounds per acre)

	May 26-June 30	July 1-Aug. 20	Aug. 21-Nov. 25	Nov. 26-March 31	April 1-May 25
Enfield v.f.s.l.					
Sodium nitrate	32.1	68.0	195.1	209.5	211.3
Ammonium sulfate	7.3	27.4	123.0	160.6	164.1
Urea	9.6	31.7	131.1	167.6	171.3
Cottonseed meal	7.9	23.7	90.4	120.3	124.4
Merrimac l. s.					
Sodium nitrate	82.9	159.0	206.7	211.9	213.8
Ammonium sulfate	9.2	49.5	89.5	94.7	96.5
Urea	32.0	92.0	132.2	137.4	138.6
Cottonseed meal	14.2	54.5	94.7	104.9	106.6
Wethersfield l.					
Sodium nitrate	37.4	107.5	189.5	217.7	220.5
Ammonium sulfate	8.0	38.3	129.5	169.8	176.8
Urea	25.0	68.5	163.7	193.6	196.0
Cottonseed meal	13.6	44.6	107.2	130.5	133.3
Merrimac sdy. l.					
Sodium nitrate	75.8	151.9	220.6	229.4	232.9
Ammonium sulfate	10.5	70.3	146.1	159.1	162.5
Urea	27.9	90.4	168.2	178.0	180.7
Cottonseed meal	10.2	59.5	125.9	140.7	144.5
No nitrogen	6.2	21.2	46.1	56.1	59.6
Average of 4 soils					
Sodium nitrate	57.1	121.6	203.0	216.2	219.7
Ammonium sulfate	8.8	46.4	122.1	146.1	150.0
Urea	23.6	70.7	148.9	169.3	171.8
Cottonseed meal	11.5	45.6	104.7	124.3	127.4

A disturbing factor in these results has been the leaching of ammonia before it had an opportunity to nitrify, especially from the sandy soils. Ammonia was determined on composite samples of the leachings during six-month periods, but was not measured for each occurrence of leaching. Detailed data were given in Appendix Table V, Bulletin **384**. Ammonia leachings were inconsequential under the nitrate of soda treatments, and from all soils and treatments in years when little leaching took place during the early summer period. On the other hand, when the June leaching was considerable, large amouts of ammonia were leached from the sulfate of ammonia treatments in inverse proportion to the base exchange capacities of the soil. Leachings of ammonia from urea were somewhat less, although greater than from the cottonseed meal treatments. The average yearly ammonia losses for the five years are summarized as Table 9.

The substantially larger losses of ammonia nitrogen from sulfate of ammonia than from urea are in agreement with results reported by Benson and Barnette[1].

[1] Benson, N. and Barnette, R. M. Leaching studies with various sources of nitrogen. Jour. Am. Soc. Agron. 31: 44-54. 1935.

TABLE 9. THE LEACHING OF AMMONIA NITROGEN FROM LYSIMETER SERIES "A"
AVERAGE YEARLY RESULTS, 1929-34
(in pounds per acre)

	May 26-Nov. 25	Nov. 26-May 25	Annual
Enfield v.f.s.l.			
Sodium nitrate	.64	1.39	2.03
Ammonium sulfate	7.47	1.56	9.03
Urea	1.23	1.04	1.27
Cottonseed meal	.33	.77	1.10
Merrimac l. s.			
Sodium nitrate	.85	.78	1.63
Ammonium sulfate	56.45	.97	57.42
Urea	21.59	.60	22.19
Cottonseed meal	3.28	.37	3.65
Wethersfield l.			
Sodium nitrate	.38	.65	1.03
Ammonium sulfate	5.17	1.63	6.80
Urea	1.34	.32	1.66
Cottonseed meal	.42	.39	.81
Merrimac s. l.			
Sodium nitrate	.59	.69	1.28
Ammonium sulfate	23.52	1.97	25.49
Urea	4.65	.50	5.15
Cottonseed meal	.71	.72	1.43
No nitrogen	.70	.65	1.35

It is reasonable to suppose that this ammonia nitrogen, leached chiefly in June, would have nitrified and subsequently leached at the same rate as the nitrogen from the sulfate of ammonia treatment residual after the June leaching, if no ammonia losses had occurred. Hence it is believed that a truer picture is presented when a correction is made on the above assumption.

Table 10 has been recalculated from Table 8, by estimated additions to all leachings subsequent to the May 26—June 30 period, in all cases where the average yearly ammonia nitrogen losses were one pound or more in excess of those from nitrate of soda treatments.

It is to be noted that even when the ammonia corrections are applied, there is incomplete liberation of nitrogen as nitrates from sulfate of ammonia, urea and cottonseed meal. There are considerable differences between soils in the total nitrification of the various materials. As would be expected, the more acid soils are poorer in nitrate liberation, particularly the extremely base-deficient Merrimac loamy sand.

Table 10. Cumulative Leaching of Nitrate Nitrogen by Periods Average Data—1929-34

Windsor Lysimeters—Series "A"

Corrected for Ammonia N. lost in leaching

(in pounds per acre)

	May 26- June 30	to Aug. 20	to Nov. 25	to March 31	to May 25
Enfield v.f.s.l.					
Sodium nitrate	32.1	68.0	195.1	209.5	211.3
Ammonium sulfate	7.3	28.3	128.1	167.3	171.0
Urea	9.6	31.8	131.8	168.5	172.2
Cottonseed meal	7.9	23.7	90.4	120.3	124.4
Merrimac l. s.					
Sodium nitrate	82.9	159.0	206.7	211.9	213.8
Ammonium sulfate	9.2	66.5	123.3	130.6	133.1
Urea	32.0	103.1	150.7	156.9	158.4
Cottonseed meal	14.2	54.9	95.6	106.0	107.7
Wethersfield l.					
Sodium nitrate	37.4	107.5	189.5	217.7	220.5
Ammonium sulfate	8.0	39.3	133.5	175.1	182.3
Urea	25.0	68.8	164.5	194.6	197.0
Cottonseed meal	13.6	44.6	107.2	130.5	133.3
Merrimac sdy. l.					
Sodium nitrate	75.8	151.9	220.6	229.4	232.9
Ammonium sulfate	10.5	79.0	165.9	180.8	184.7
Urea	27.9	91.9	171.6	181.6	184.4
Cottonseed meal	10.2	59.5	125.9	140.7	144.5
No nitrogen	6.2	21.2	46.1	56.1	59.6
Average of 2 sandy soils					
Sodium nitrate	79.4	155.4	213.6	220.6	223.3
Ammonium sulfate	9.9	72.7	144.6	155.7	158.9
Urea	29.9	97.5	161.2	169.2	171.4
Cottonseed meal	12.2	81.3	110.7	123.3	126.1
Average of 2 loam soils					
Sodium nitrate	34.7	87.7	192.3	213.6	215.9
Ammonium sulfate	7.6	33.8	130.8	171.2	176.7
Urea	17.3	48.5	146.3	181.5	184.6
Cottonseed meal	15.7	34.2	98.8	125.4	128.9
Average of 4 soils					
Sodium nitrate	57.1	121.6	203.0	216.2	219.7
Ammonium sulfate	8.8	53.3	137.7	163.5	167.8
Urea	23.6	73.9	154.6	175.4	178.0
Cottonseed meal	11.5	45.7	104.8	124.4	127.5

If the total nitrate leaching, as corrected, is taken as a measure of relative availability and nitrate of soda is considered as 100 percent, the average relative availability on the four soils is as follows:

Nitrate of soda	100.0%
Urea	81.0%
Sulfate of ammonia	76.4%
Cottonseed meal	58.0%

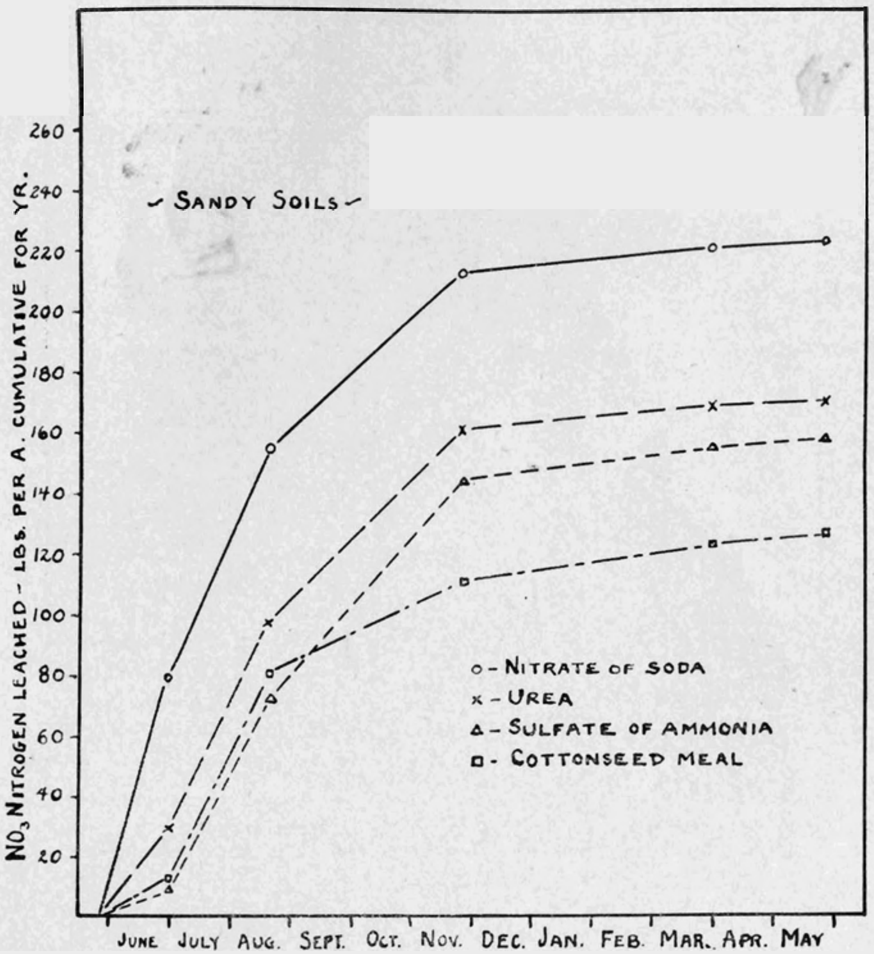

Figure 12. Progressive leaching of nitrate nitrogen from two sandy soils as treated with various materials, based on average data by seasons, 1929-1934.

The progressive leaching of nitrate nitrogen from the various materials is plotted in Figure 12, for the two sandy soils, and in Figure 13, for the two loamy soils.

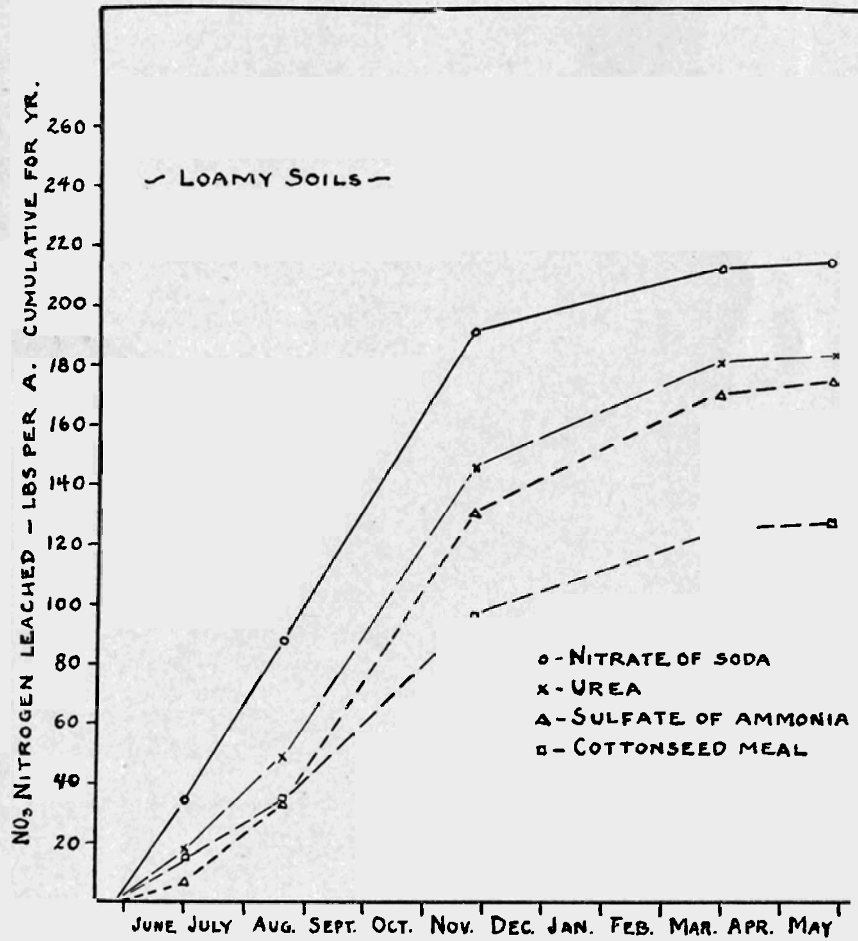

FIGURE 13. Progressive leaching of nitrate nitrogen from two loamy soils, as treated with various materials, based on average data by seasons, 1929-1934.

ESTIMATED RATE OF NITROGEN LIBERATION BASED ON LEACHING DATA

THE concept of proportionate leaching of soil nitrates developed earlier in this paper, and presented graphically as Figures 7 and 8, may be employed in the estimation of rates of nitrate liberation from non-nitrate sources of nitrogen. It is reasonable thus to interpolate the amount of nitrate nitrogen existing in the soil, prior to leaching, from the amount leached during a given period by a given volume of drainage water. A basis for computing the progressive liberation of nitrate nitrogen during the season may also be worked out in terms of daily rates of nitrate formation during the months immediately following fertilizer application.

The distribution of nitrate nitrogen leachings, by periods, (based on ammonia-corrected data) for the various soils is given in Table 11.

TABLE 11. DISTRIBUTION OF NITRATE NITROGEN LEACHING BY PERIODS. AVERAGE DATA 1929-34. BASED ON AMMONIA-CORRECTED DATA. Windsor Lysimeters—Series "A" (in pounds per acre, by periods)

	May 26-June 30	July 1-Aug. 20	Aug. 21-Nov. 25	Nov. 26-Mar. 31	Apr. 1-May 25
Enfield v.f.s.l.					
Sodium nitrate	32.1	35.9	127.1	14.4	1.8
Ammonium sulfate	7.3	21.0	99.8	39.2	3.7
Urea	9.6	22.2	100.0	36.7	3.7
Cottonseed meal	7.9	15.8	66.7	29.9	4.1
Merrimac l. s.					
Sodium nitrate	82.9	76.1	47.7	5.2	1.9
Ammonium sulfate	9.2	57.3	56.8	7.3	2.5
Urea	32.0	71.1	47.6	6.2	1.5
Cottonseed meal	14.2	40.7	40.7	10.4	1.7
Wethersfield l.					
Sodium nitrate	37.4	70.1	82.0	28.2	2.8
Ammonium sulfate	8.0	31.3	94.2	41.6	7.2
Urea	25.0	43.8	95.7	30.1	2.4
Cottonseed meal	13.6	31.0	62.6	23.3	2.8
Merrimac sdy. l.					
Sodium nitrate	75.8	76.1	68.7	8.8	3.5
Ammonium sulfate	10.5	68.5	86.9	14.9	3.9
Urea	27.9	64.0	79.7	10.0	2.8
Cottonseed meal	10.2	49.3	66.4	14.8	3.8
No nitrogen	6.2	15.0	24.9	10.0	3.5
Average of 2 sandy soils					
Sodium nitrate	79.4	76.1	58.2	7.0	2.7
Ammonium sulfate	9.9	62.8	71.9	11.1	3.2
Urea	29.9	67.6	63.7	8.0	2.2
Cottonseed meal	12.2	69.1	29.4	12.6	2.8
Average of 2 loam soils					
Sodium nitrate	34.7	53.0	104.6	21.3	2.3
Ammonium sulfate	7.6	26.2	97.0	40.4	5.5
Urea	17.3	31.2	97.8	35.2	3.1
Cottonseed meal	15.7	18.5	64.6	26.6	3.5
Average of 4 soils					
Sodium nitrate	57.1	64.5	81.4	13.2	3.5
Ammonium sulfate	8.8	44.5	84.4	25.8	4.3
Urea	23.6	50.3	80.7	20.8	2.6
Cottonseed meal	11.5	34.2	59.1	19.6	3.1

The combined data for the two sandy soils and for the two loam soils are sufficient for the purpose of revealing the rates of nitrate liberation from the three non-nitrate materials used in this experiment.

The periodic leaching of nitrate nitrogen from the two pairs of soils has been accomplished by average amounts of drainage water as shown in Table 12.

TABLE 12. DISTRIBUTION OF DRAINAGE WATER FLOW BY PERIODS
AVERAGE DATA 1929-34
Windsor Lysimeter Series "A"
(in acre inches)

	May 26-June 30	July 1-Aug. 20	Aug. 21-Nov. 25	Nov. 26-March 31	April 1-May 25
Average of 2 sandy soils					
(Merrimac sdy. l. and Merrimac l. s.)					
Sodium nitrate	1.13	1.15	3.63	7.30	2.32
Ammonium sulfate	1.12	1.16	3.67	7.35	2.32
Urea	1.14	1.20	3.64	7.06	2.36
Cottonseed meal	1.40	1.30	3.78	7.07	2.40
Average of 2 loam soils					
(Enfield v.f.s.l. and Wethersfield l.)					
Sodium nitrate	.91	.74	3.26	6.78	2.22
Ammonium sulfate	.83	.69	3.12	6.79	2.12
Urea	.84	.70	3.18	6.71	2.13
Cottonseed meal	1.02	.76	3.16	6.70	2.15

The data in Tables 11 and 12, and application of the proportionate leaching graphs in Figure 8, permit computations of probable maxima of nitrate nitrogen accumulations during each period. The quantities of nitrate nitrogen liberated during each period are obtained from the amounts by which these maxima exceed the calculated residues from the leachings of the previous period.

The results thus obtained showed an apparent disappearance of nitrate nitrogen under the cottonseed meal treatment during the third period (August 21—November 25) in the sandy soils, and obviously abnormally high nitrate liberations during the first period, followed by abnormally low nitrification during the second period for both urea and cottonseed meal in the loam soils. In all other cases the above scheme of computation indicated amounts of nitrification in reasonable accord with the known facts concerning the rates of availability of these materials.

Arbitrary adjustment has been made in case of the obviously erratic results noted in the preceding paragraph, and the progressive liberation of nitrate nitrogen during the year has been plotted as the smoothed curves shown in Figure 14.

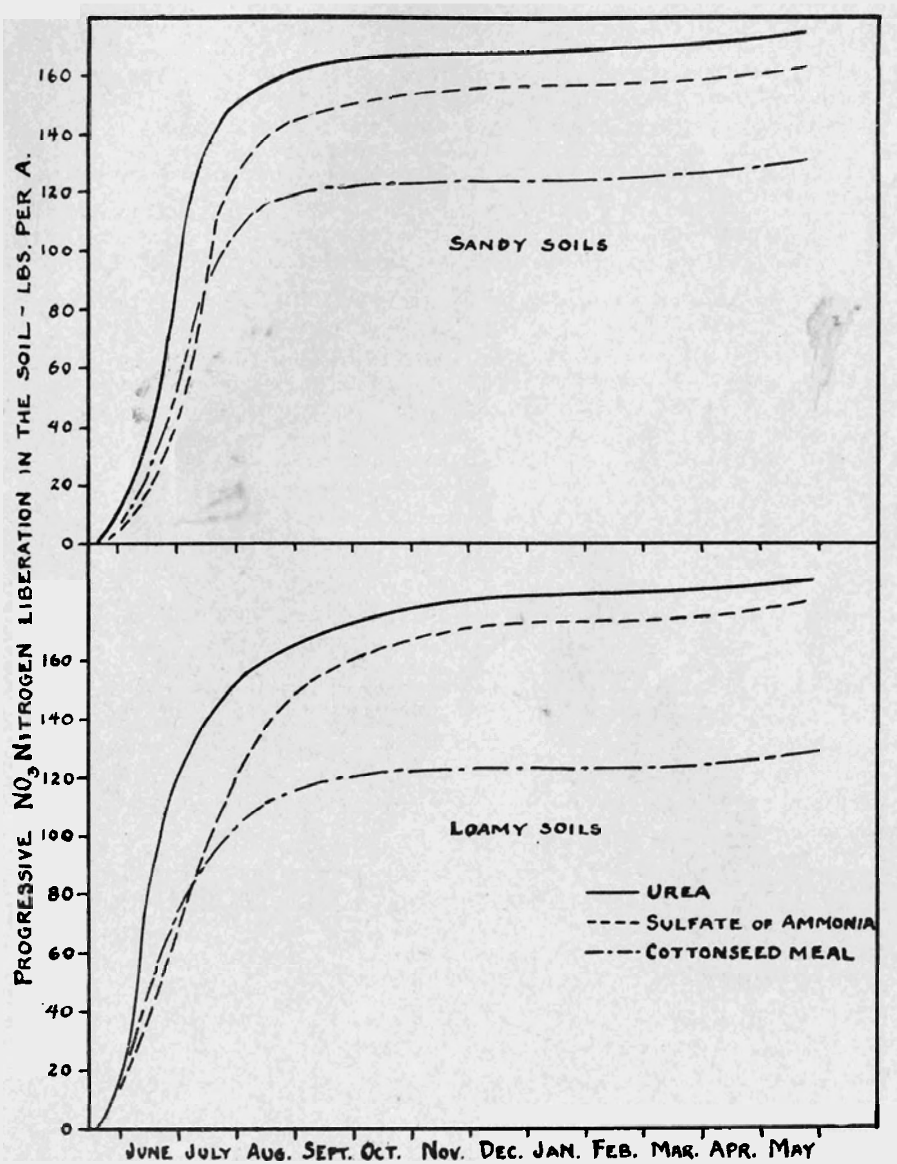

FIGURE 14. Progressive liberation of nitrate nitrogen from urea, sulfate of ammonia and cottonseed meal, based on lysimeter data for 1929-1934.

By means of graphic interpolation, the progressive nitrification of the fertilizer materials has been developed in terms of daily rate of nitrate nitrogen liberation per 100 pounds of fertilizer nitrogen. Figures 15 and 16 are plotted on this basis. Only the first four months after fertilizer application are here considered since the subsequent rate of nitrification is too slow to be clearly represented on this scale of plotting.

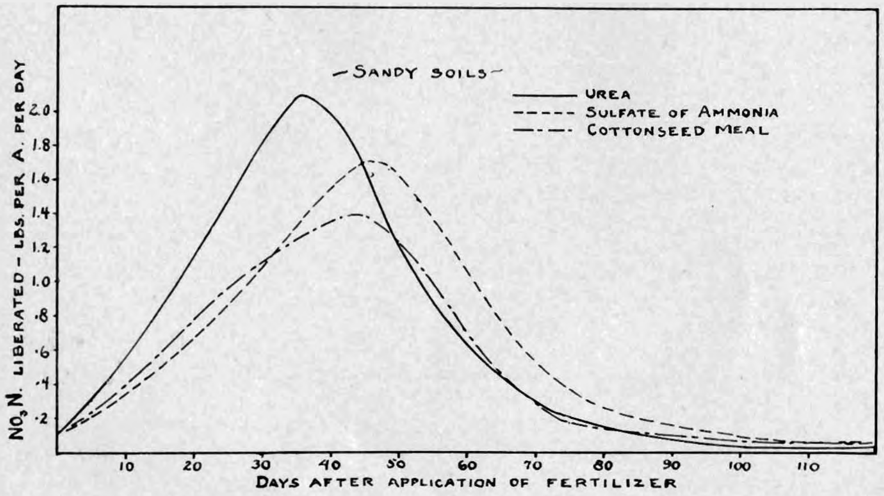

FIGURE 15. Average daily rate of nitrate nitrogen liberation, in sandy soils, from urea, sulfate of ammonia and cottonseed meal, based on lysimeter data for 1929-1934.

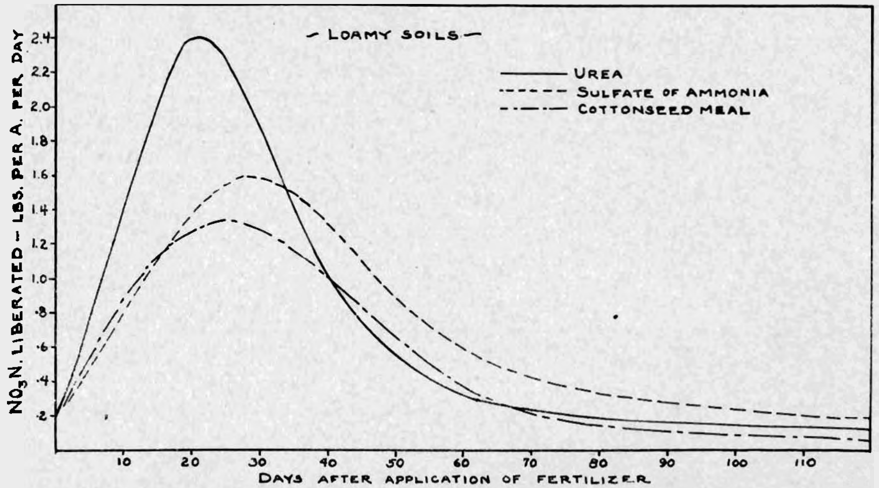

FIGURE 16. Average daily rate of nitrate nitrogen liberation, in loamy soils, from urea, sulfate of ammonia and cottonseed meal, based on lysimeter data for 1929-1934.

The rates of nitrogen assimilation of Havana seed tobacco have been previously studied by the authors.* The data have been recalculated in order to show the daily nitrogen needs of the crop and are graphically portrayed in Figure 17.

These graphs indicate that the peak rate of nitrification is attained in a considerably shorter time on the heavier soils. This is doubtless due to their more generally favorable moisture status and related conditions desirable for microbiological activity. Perhaps the same factors also explain the more gradual decrease in rate of nitrogen liberation in the latter part of the season, since considerable secondary nitrification from the biologically synthesized materials would be expected to occur.

On both soil conditions, urea is more r pidly and completely nitrified than the other two materials. Sulfate of ammonia and cottonseed meal are not greatly different in their earlier rates of nitrification. However, the former material is somewhat slower at first, probably due to the inhibiting effect of its strongly acid characteristics, previously discussed in detail in Bulletin 384 of this Station. The ultimate peak rate for sulfate of ammonia is considerably higher than for cottonseed meal, since the latter material is much less completely nitrified.

The much slower rate of nitrification shown by sulfate of ammonia as compared with urea is probably largely due to the greater acid effect of the former material, both being used without lime adjustment in this experiment. A further series of lysimeter tanks, in operation since 1934, has provided for comparisons both with and without correction of the acid effects of the fertilizers. The data show earlier peaks in rate of nitrification when the materials are neutralized by lime, and that urea becomes only slightly more rapidly nitrified than sulfate of ammonia under such conditions. These trials (Lysimeter Series "D") will be reported in detail in a later publication.

*Morgan, M. F. and Street, O. E. Rates of growth and of seed tobacco. Jour. Agr. Res. 51: 163-172. 1935.

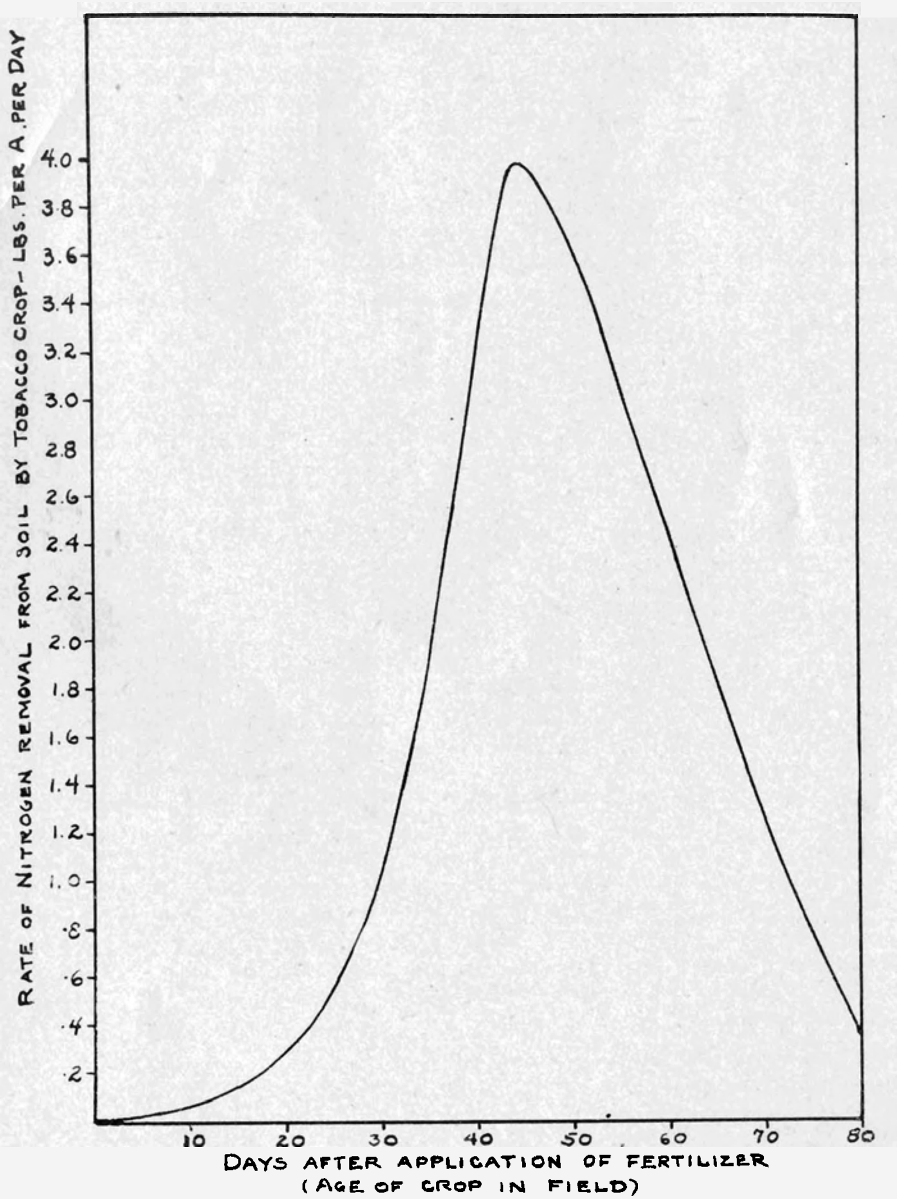

FIGURE 17. Rate of nitrogen removal from soil by a normally growing crop of Havana seed tobacco, as related to age of crop in the field.

INTERPRETATION OF RESULTS IN TERMS OF FERTILIZER PRACTICES

THE results reported in this bulletin have been obtained from uncropped soils of shallow depth (7 inches), under admittedly artificial conditions with respect to moisture relationships. The soils in the lysimeter tanks dry out more rapidly than if lying fallow under field conditions. However, the water deficit attained during the summer period approximates that of a field soil under a tobacco crop. This feature helps to make the results more applicable to practical problems of nitrogen fertilization, particularly for tobacco.

During the experimental years the prevailing weather conditions have been drier than normal; hence much greater nitrate loss by leaching may have taken place during the growing season. This was strikingly illustrated in the summer of 1938 when seven acre inches or more of drainage water passed through the soil during the first two months after the fertilizer was applied, based on data obtained on lysimeter experiments in progress at that time. All of the indications herein reported were fully confirmed, both by the lysimeters and by the disastrous effects on the field crop. Significant features of the 1938 results have been given in Bulletin 422 of this Station.*

The principles developed in the preceding pages make it possible to follow the course of the present and potential available nitrogen supply in the soil through the season. The quantities of various nitrogenous ingredients in the fertilizer are known. The amount and distribution of rainfall are matters of record.

Provision must be made for adequate amounts of available nitrogen to meet the demands of the crop at all times, yet the amounts of nitrate nitrogen remaining in the soil at harvest time must be comparatively small, else the quality of the crop will be adversely affected.

When the fertilizer contains some nitrate nitrogen, as nitrate of soda or nitrate of potash, this is entirely available, but is subject to leaching from the very beginning of the season. If, for instance, 40 pounds of nitrate nitrogen per acre were used, and a 4-inch rain occurred about June 1, sandy soils might lose as much as 35 pounds of this nitrogen and the application would need to be repeated. The non-nitrate materials would lose little nitrogen by leaching so early in the season, and if no further leaching occurs, there is possibly enough potentially available nitrogen to carry the crop through the season.

Let us suppose that no leaching occurred in June, but that a 4-inch rain fell about July 1, preceded by several lighter rains. By this time the 40 pounds of nitrate nitrogen, plus about 50 pounds of nitrate nitrogen liberated from organic materials such as cottonseed meal and plus about 10 pounds from the soil itself, have supplied 100 pounds of available nitrogen per acre. The crop has taken up only about 15 pounds by this time, leaving 85 pounds subject to leaching, of which at least 75 pounds would be washed out of the soil by a 4-inch rain. The original 160 pounds of organic

*Morgan, M. F. and Street, O. E. Losses of fertilizer constituents by leaching during an abnormally wet growing season. Bul. 422: 6-16. 1939.

nitrogen can liberate not more than about 40 pounds of additional nitrogen before the end of the growing season. Even with a liberal allowance of 10 pounds of additional nitrogen liberation from the older organic nitrogen residues of the soil itself, there is now not more than 60 pounds of nitrogen in sight to supply a crop needing 105 pounds to complete its growth. It is customary to apply about 40 pounds of nitrogen as nitrates after such leaching rains. Yet even if no further leaching occurs, this is not quite sufficient for a normal yield.

A somewhat different situation is presented on a soil of more loamy character, as a consequence of the weather conditions noted in the preceding paragraph. The nitrification of the cottonseed meal has proceeded farther before leaching, liberating about 70 pounds of nitrate nitrogen per acre by July 1. This amount, plus the original 40 pounds from the fertilizer and 10 pounds nitrified from the soil itself, gives a total of 120 pounds, depleted by the crop to about 105 pounds. The 4-inch rain on a previously saturated loam soil may be expected to leach about 80 pounds, leaving 25 pounds of nitrate nitrogen in the soil. Further nitrification from the soil and the cottonseed meal can provide only 60 pounds; hence there is a total of 85 pounds of present or potentially available nitrogen, with a crop needing 105 pounds for full yield. If no further leaching rains occur, this may provide a crop of good quality, but the weight will certainly be light unless at least 20 pounds of nitrate nitrogen per acre are added as a side-dressing.

No two seasons are alike, and unless careful attention is given to the fertility balance in the soil, no two crops will be similar in yield and quality. A fertilizer application that provides too much nitrogen for good quality in a very dry season may be totally insufficient in a very wet one. Cool weather in the early part of the growing season retards growth of the crop and similarly delays the rate of liberation of nitrates for organic nitrogen sources, including urea. The amount of rain that must fall before leaching begins is much greater after dry, hot periods.

Soils recently manured or cropped to legumes, or well supplied with fairly decomposable nitrogen, can supplement the available nitrogen provided by the fertilizer to a greater degree than soils poor in humus and under continuous cropping without manure or legumes. Such factors make it difficult to estimate closely the balance between nitrate nitrogen accumulation on the one hand and crop removal and leaching on the other. However, it is believed that the picture of leaching presented in this bulletin will serve to remove much of the uncertainty concerning the performance of fertilizer nitrogen in the soil.

SUMMARY

FOUR soils have been studied with respect to the quantity and composition of the drainage water passing through their surface soil layers (7-inch depth) during the five-year period: 1929-1934. This bulletin is a second and final report on this series (Windsor Lysimeter Series "A"), following Bulletin 384 of this Station. Particular attention is here given to the amounts and distribution of leaching during various seasons of the year, both as to volume of drainage water and quantities of nitrogen thus lost from the soil. Two relatively sandy soils, the Merrimac loamy sand and Merrimac sandy loam types, and two relatively loamy soils, the Enfield very fine sandy loam and Wethersfield loam types, were included in this experiment. Each soil was investigated with respect to nitrogen losses by leaching effected from the following sources of fertilizer nitrogen: nitrate of soda, sulfate of ammonia, urea and cottonseed meal, each applied at the rate of 200 pounds of nitrogen per acre, on May 26 of each year.

The weather conditions during the five years of this study were below normal in rainfall, and included marked variations from year to year, both with respect to precipitation and temperature. Most of the characteristic features of southern New England weather have been encountered, although the duration of the experiment has been too short to give a true average of conditions that determine the distribution of the leaching of drainage water through the soil. However, the cumulative soil changes resulting from the fertilizer treatments have made it inadvisable to continue this series for a longer period.

The quantity of drainage water resulting from precipitation during a storm period is most affected by soil characteristics during the warmer months when the increased daily rate of evaporation produces rapid saturation deficits in soil moisture. Sandy soils with low moisture contents, even in a saturated state, evaporate much less water per unit area than heavier soils; hence when heavy rains occur, smaller amounts of precipitation are required to restore them to a state of saturation, after which any further rainfall passes through the soil. The Enfield soil used in this series was unusually resistant to leaching, chiefly as a consequence of rapid evaporation of its internal moisture. Average summer rates of evaporation, under the conditions of this study, have varied from .08 acre inches of water per day in case of the Merrimac loamy sand to .096 acre inches from the Enfield soil, with the other two soils at intermediate rates. Rates of evaporation during the cooler months are approximately one-half of the above amounts. The extremes with respect to percentages of total precipitation leached through the surface soil are 34.8 percent in case of the Enfield soil, and 44.6 percent in case of the Merrimac loamy sand.

Of the four fertilizer materials used, only cottonseed meal affected the amount of water leached in excess of evaporation. This material resulted in decreased evaporation to the extent of .332 acre inches during the average midsummer period of 85 days, from May 26 to August 20.

When the fertilizer treatment supplies all of the nitrogen in a readily leachable form, as nitrate of soda treatment, the nitrates are quantitatively leached from the soil in direct relationship to the volume of drainage water passing through the soil, except for a brief initial period required to

displace soil water of slight nitrate concentration from the lower portion of the soil mass. After the drainage water attains a maximum of nitrates, further increments of leaching become more and more dilute. However, there is evidence that some nitrate nitrogen may be partially retained within the soil crumbs if a soil has good structure development such as Wethersfield.

The progressive removal of nitrates from the soil by leaching is a logarithmic function of the amount of water passing through the soil, since a given increment of drainage water causes the leaching of a definite proportion of the amount of nitrate nitrogen left in the soil by previous increment. Thus, 50 percent of the nitrate nitrogen residue was leached by 0.95 acre inches of drainage water from the sandy soils, and by 1.40 acre inches from the loamy soils.

Analysis of the data presented in this bulletin permits a fair estimation of the relative amount of nitrate nitrogen that may be expected to leach from the soil by a given amount of rainfall occurring during a storm period. This relationship has been expressed by means of suitable graphs.

When the fertilizer material supplying nitrogen to the soil is not initially in the form of nitrates, as in case of nitrate of soda, the ammonia nitrogen either in the fertilizer as such or developed by hydrolysis or biological decomposition must be subjected to nitrification processes in the soil before it is materially affected by leaching. However, on light sandy soils, significant amounts of ammonia nitrogen may be leached if heavy rains occur during the first few weeks after the fertilizer is applied. Leachings during the early summer period thus remove much smaller relative proportions of nitrogen from non-nitrate materials applied to the soil. However, since the total amounts of nitrate nitrogen formed from sulfate of ammonia, urea or cottonseed meal are less than 100 percent of the amount of nitrogen in the fertilizer, a nitrate material must be somewhat more exhausted from the soil by leaching before the concentration in the soil is at the same level as attained by nitrification from an equal amount of nitrogen in other sources.

Urea is more rapidly leached from the soil than either sulfate of ammonia or cottonseed meal. The latter two materials are similar with respect to their rapidity of nitrification. However, a given quantity of nitrogen in the form of cottonseed meal develops a much smaller amount of nitrate nitrogen in the course of the year. This was consistently shown by all four of the soils. Less than two-thirds of the nitrogen from cottonseed meal has become available in the soil in the form of nitrates in these trials. Both urea and sulfate of ammonia have given up approximately four-fifths of their nitrogen as nitrates except on the Merrimac loamy sand where leaching of ammonia nitrogen was a serious factor in some instances.

Nitrification has been more rapid on the two more loamy soils used in these trials. The more favorable moisture conditions during critically dry periods are probably the controlling factor in this difference, as compared with the more sandy soils.

The results of this series of lysimeter experiments furnish the basis for a better understanding of the factors involved in the use of large amounts of nitrogenous fertilizers, such as practiced for tobacco in the Connecticut

Valley. The use of 200 pounds of nitrogen per acre, supplying 40 pounds immediately available as nitrates and the balance as organic nitrogen, is the common practice in this area. In seasons when the rainfall is abundant but not excessive, this provides nitrates in desirable quantity during the period of most rapid demand by the crop, with little left in the soil at harvest time. Nitrate nitrogen applied before planting time may often be leached from the soil during early summer rains. However, unless the leaching is severe during July, the organic nitrogen is able to build up the soil to a favorable level by the time the crop needs it most. This may not be quite sufficient; hence some nitrate nitrogen is a desirable supplement to the natural organic nitrogenous materials. If a more quickly and completely available source of nitrogen, such as urea, is used as a partial substitute for organic meals, fertilizer nitrates are less likely to be needed, and may be definitely objectionable in dry seasons. The total amount of nitrogen supplied in the fertilizer before planting should also be somewhat diminished, with side-dressings of nitrate nitrogen if weather conditions are favorable for leaching.

A summer rain of less than an inch rarely produces leaching unless the soil is practically saturated by rains occurring during the past two days. After a week or more without rain, a 2-inch precipitation causes little or no leaching on loam soils, but may seriously deplete the available nitrogen from sandy soils. Severe storms with a rainfall of 4 inches or more within a three-day period remove from 50 percent to 75 percent of the nitrate nitrogen from loamy soils, and from 75 percent to 90 percent from the sandier soils. However, if the leaching takes place during the first two or three weeks after the fertilizer is applied, a comparatively small proportion of the nitrogen from such non-nitrate materials as urea, cottonseed meal or sulfate of ammonia will be lost, even though the rainfall is quite heavy. Severe leaching occurring six weeks or more after the fertilizer is applied may practically exhaust the available nitrogen potentiality of the fertilizer, irrespective of the form in which the nitrogen is supplied, as witnessed by the disastrous consequences of the July rainfall in 1938.

Large accumulations of nitrate nitrogen in the soil, in excess of the immediate needs of the crop, may be practically avoided in case of slow growing, long season crops and are rarely found under grass cover. However, it is probably not possible to provide tobacco and similar plants with all the nitrogen they need during the period of their most rapid growth without building up a considerable previous surplus of nitrates. If this is depleted by leaching, it must be replaced as quickly as possible, else the crop must suffer.