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A Study on the Influence of Climate Upon the Nitrogen and Organic Matter Content of the Soil

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ABSTRACT

Difficulties encountered in the maintenance of nitrogen and organic matter in Missouri soils led to the study of climate as a possible factor controlling the nitrogen level in soils. After suitable climatic maps of the United States had been constructed and a large number of nitrogen analyses correlated with temperature and moisture it was found that climate exerts a dominating influence on the amount of total nitrogen in soils. With increasing temperature soil nitrogen and organic matter decrease, while with increasing moisture values they increase. It is possible to construct an idealized nitrogen-climate-surface for the soils of the Great Plains area and the prairie region. A causal relationship between the nitrogen-temperature relation on the one hand, and soil organic matter maintenance and low corn yields in southern regions on the other, has been suggested.

A Study on the Influence of Climate Upon the Nitrogen and Organic Matter Content of the Soil

HANS JENNY

INTRODUCTION

The virgin black prairie soils, rich in nitrogen and organic matter, are among the most fertile soils known, but their productivity is by no means a constant. Continuous cropping under ordinary farming practices lessens the fertility, the nitrogen content of the soil decreases and the crop yields diminish. On Sanborn Field, at the Missouri Experiment Station, the average corn yields of untreated plots declined from 28.4 bushels during the 10-year period 1889-1898 to only 16.9 bushels during the 10-year period 1919-1928. Naturally, the agricultural experiment stations are paying special attention to this important problem of nitrogen economy, and improved methods of soil management are constantly being sought. The Missouri Experiment Station has been working for a number of years on this problem of nitrogen maintenance. Attempts have been made to increase the rather low nitrogen content of some of the Missouri soils by application of manure and green manure in various schemes of rotation. Careful analyses show, however, that it has not been possible to build up soil nitrogen on a profitable basis. Even under rather large applications of nitrogen the increase is small. These results are in agreement with the observations of many other experiment stations, especially those in the South. On the other hand, several institutions in the northern states have indicated a definite increase in soil nitrogen under good systems of soil management.

Since similar methods of soil treatment seem to give different results in different parts of the country, and since 20 or 30 years of nitrogen applications do not materially increase the nitrogen content of many soils, some important, yet unrealized disturbing factor or factors, must be operative in the control of the soil nitrogen level. At the beginning of the study here reported, the idea was suggested that the climate might be such a determining factor. If one remembers that the decomposition of organic matter in the soil is primarily a microbiological process, it becomes quite evident that such climatic factors as moisture and temperature must play a leading part in establishing the natural nitrogen equilibrium. The results of a two year study, in which about 2000 nitrogen analyses from all parts of the United States have been correlated with climate, show that moisture and temperature effects can satisfactorily account for some of the important difficulties encountered in the experimental field work on soil nitrogen relationships.

THE GENERAL EXPRESSION OF THE NITROGEN-CLIMATE RELATIONSHIP*

The nitrogen content of any soil is intimately associated with the history of that soil, or technically speaking, it is a function of the various factors which are operative during the process of soil development. Such factors are parent material, topography, climate, vegetation, microbiological soil population, and cultivation. We do not know, *a priori*, whether these factors exert equal influences, or whether some are more effective than others in controlling the soil nitrogen level. In concentrating our interest on the climatic factor alone, it will, therefore, be necessary to have all the remaining soil forming agencies constant. Keeping this restriction in mind, the general expression for the nitrogen-climate relationship is adequately written as follows:

$$\text{Soil nitrogen} = f\ (\text{climate}) \qquad \text{(I)}$$

which is simply the mathematical way of saying that the nitrogen content of the soil depends on the climate or is a function (f) of the climate[20].†

From the point of view of soil formation, the main climatic factors are temperature, precipitation, and evaporation. The two latter terms are often combined into a single quotient, the so-called "humidity factor" or "moisture factor", which allows the complex expression "climate" to be represented by the precise terms temperature and moisture. Thus:

$$N = f\ (T, H) \qquad \text{(II)}$$

where N means total nitrogen content of the soil, T, temperature, and H, humidity factor, eg. the ratio of precipitation to evaporation. The entire investigation has thus been limited to the interaction of temperature and moisture on the nitrogen equilibrium in soils. Both climatic factors are considered to be independent variables.

An essential characteristic of equation (II) is the fact that all three variables N, T, H, can be measured and expressed numerically, which immediately suggests the search for a so-called "equation of state" that is the mathematical expression of the law which possibly governs the climatic distribution of soil nitrogen.[25]

Writing equation (II) in differential notation gives:

$$dN = \left(\frac{\partial N}{\partial T}\right)_H dT + \left(\frac{\partial N}{\partial H}\right)_T dH \qquad \text{(III)}$$

In order to solve this equation one must obviously know the nature of the two partial differential coefficients $(\partial N/\partial T)_H$ and $(\partial N/\partial H)_T$, which may be obtained either by deductive or inductive methods. After enumeration of these partial differential coefficients, it is perhaps possible to integrate equation (III), thus arriving at a specific expression of the nitrogen-climate relationship.

*The author is fully aware of the limitations of the speculative scientific method applied in this study. While it is possible that further investigations will reveal other variables that must be considered, the results obtained seem to justify this particular mode of treatment.

†Superscript numerals refer to the bibliography, page 65.

$(\partial N/\partial T)_H$ is the first differential coefficient of the so-called *nitrogen-temperature relation*, that is the variation of soil nitrogen with temperature in regions of equal humidity factors.
$(N\partial/\partial H)_T$ is the first differential coefficient of the so-called *nitrogen-humidity factor relation*, that is the variation of soil nitrogen with humidity factors in regions of equal temperature. Before attempt is made to investigate the nature of the two separate functions, a careful analysis of the temperature and moisture conditions of the regions to be studied becomes necessary. Climatic maps must be constructed which permit one to bring together analyses of soil samples collected either along lines of equal temperatures (isotherms) or along lines of equal humidity factors (isonotides).

THE CLIMATE OF THE UNITED STATES IN REGARD TO SOIL FORMATION

Soil scientists often distinguish between air climate and soil climate. By the latter they mean the temperature and moisture conditions of the soil itself while the former refers to those measured at some distance above the ground by the meteorological stations. Data on soil climate are very meagre. It is known that the march of soil temperatures runs approximately parallel to the march of the air temperatures, but relatively few experimental figures are available. Records on soil moisture are still scantier. As a consequence, in the present study, soil climate has been disregarded.

Temperature

The choice of the temperature unit in soil climate studies has to be decided on first. Shall the nitrogen content of the soil be studied in relation to the mean annual temperature or to the frost-free season or to daily temperature

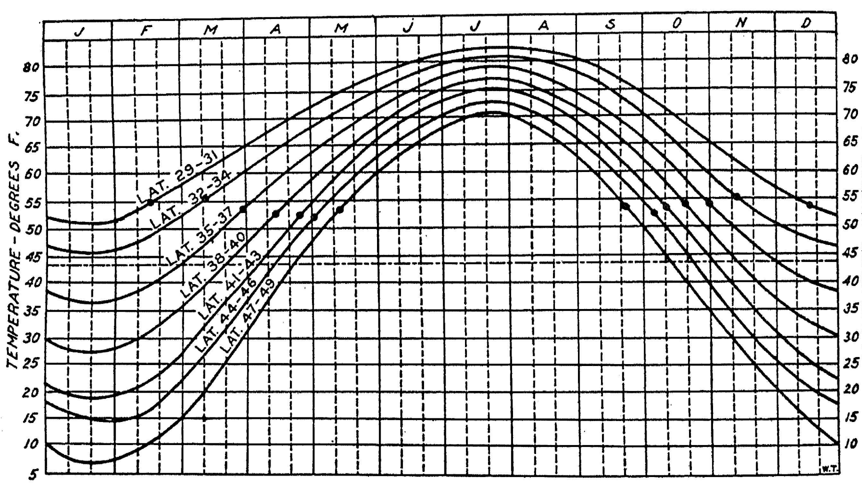

Fig. 1. Annual march of temperature of the investigated region. (After Kincer).

summations or to some other criterion of the heat effect? At first, the number of months having mean temperatures above freezing point was chosen, but later the mean annual temperature was found to be more practical and easier to be obtained. Its use, however, is restricted to regions having similar marches of annual temperatures. Figure 1 shows the annual march of temperature of the areas investigated[30]. All temperature figures used were taken from publications of the United States Weather Bureau.[75] Unfortunately the Bureau does not publish maps showing annual isotherms. Those had to be constructed especially for the present investigation. Annual isotherms of 4°, 12°, 20°C. are shown in Figure 3.

Moisture (Humidity factors)

Rainfall alone is not a satisfactory index of soil moisture, because of the great variations in evaporation, irrespective of rainfall, which offset the effect of the precipitation. An examination of the evaporation map published by the Weather Bureau in the Atlas of American Agriculture[29] shows that in the warm season alone (April to September) evaporation varies from 25 to 88 inches in various parts of the United States.

A. Penck[57] uses precipitation and evaporation in the classification of climates. He sets the boundary between arid and humid regions at that locality where precipitation and evaporation are equal, in other words, where the precipitation-evaporation ratio is unity. The great advantage of this procedure lies in the possibility of characterizing the transition from arid to humid climates by a series of consecutive numbers. Unless general climatic terms, such as arid, humid, cold, tropical, and the like, are replaced by such consecutive numbers, no quantitative functional correlation between soil nitrogen and climate can be hoped for.

As early as 1905, E. N. Transeau[73] constructed a precipitation-evaporation map of the eastern United States. This map was based on Russell's evaporation measurements made during 1877-1878[60]. One might use Transeau's map for the present study, except for two reasons. First, the map of Transeau rests on evaporation measurements of one year only, and second, the map cannot be compared with humidity factor maps of other countries, because of differences in observational methods. A search must, therefore, be made for an adequate substitute.

Lang[33] suggested the so-called *rainfactor* (RF) in which the evaporation is replaced by temperature, since for the temperature magnitudes in question, the vapor tension of water is nearly a linear function of temperature. Following Lang's suggestion, rainfactors were calculated for the present study for over 2000 meteorological stations by using the data collected by the United States Weather Bureau[75] and a rainfactor map of the United States was drawn as shown in Figure 2. A similar world map was designed by Hirth.[14]

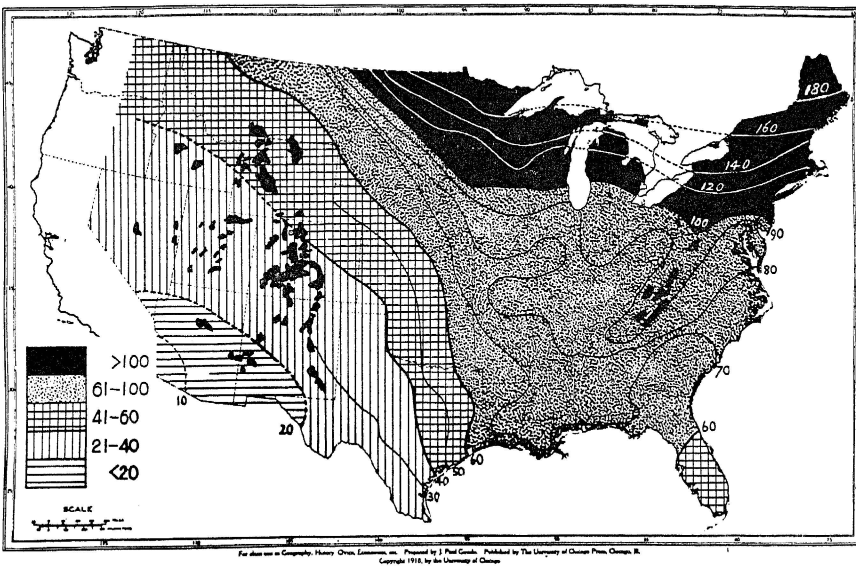

Fig. 2.—Map of rain factors (precipitation-temperature quotients) of the United States. The rain factor is only a fair substitute for the precipitation-evaporation ratio, but can be calculated for most of the meteorological stations and is helpful for orientation purposes.

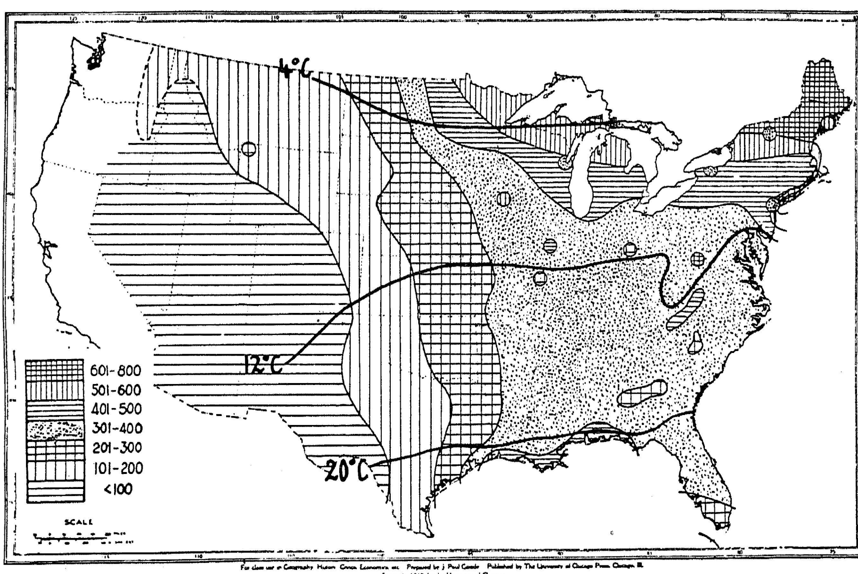

Fig. 3.—Humidity factor map (N. S. Q.) of the United States, and annual isotherms of 4°, 12°, 20°C. Th N. S. Quotient is a satisfactory substitute for Transeau's precipitation-evaporation ratio and has the advantage of international application.

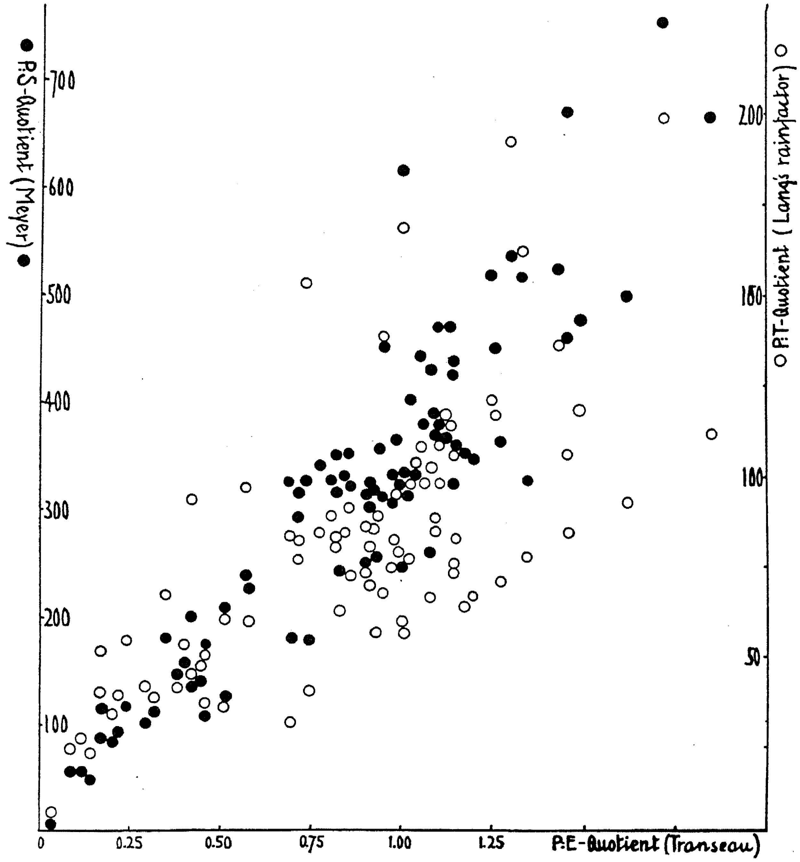

Fig. 4.—Graphical comparison between precipitation-evaporation quotient of Transeau, precipitation-saturation deficit quotient of Meyer (N. S. Q.), and precipitation-temperature quotient of Lang (Rain Factor).

A further step in securing evaporation substitutes was made by A. Meyer[38], who argued that not only temperature but also air humidity regulates the evaporation magnitudes. He formed the so-called *N. S.* Quotient*, which is the ratio of precipitation to the absolute saturation deficit of the air.† Because Meyer published a N. S. Q. map for Europe only[38], a corresponding map of the United States had to be drawn. It is based on 144 N. S. Quotients and has exactly the same shading (see Figure 3) as Meyer's map of Europe. A detailed summary of all American values for precipitation, rainfactors and N. S. Quotients is given in Table 1.

A graphical comparison (Figure 4) of the Transeau moisture index with the rainfactor and the N. S. Quotient reveals clearly that with an increasing

*N. S. in German is an abbreviation for Niederschlag and Sattigungsdefizit. In English and French we would use the term P. S. Quotients.

†Objections against the use of the saturation deficit of the air as an index for evaporation were brought out by E. B. Livingston.[34]

moisture index the two substitutes also increase, the values being distributed approximately along a straight line. On the other hand, the figure indicates that the dispersion of the N. S. Q. is smaller than that of the R. F., a credit which must be given to the N. S. Quotient. Furthermore, when one remembers that Transeau's ratio consists of evaporation measurements for a single year only, while the N. S. Quotient includes 20-50 years of air humidity measurements, it is probably safe to conclude that the diversion of the N. S. Quotient points from a perfect straight line is due to the incompleteness of Transeau's data. Averages of repeated evaporation measurements would undoubtedly reduce the scattering. In other words, the N. S. Quotient seems to furnish a satisfactory substitute for the true precipitation-evaporation ratio.

Again the question arises as to whether annual, seasonal, or monthly humidity factors should be correlated with soil nitrogen analyses. For the sake of simplicity, annual N. S. Quotients were chosen, which so far have given good results. In more detailed studies and especially if the investigations are to be extended over other continents, the seasonal distribution of the humidity factors perhaps must be taken into consideration.

TABLE 1.—SUMMARY OF THE CLIMATOLOGICAL DATA FOR THE UNITED STATES

State	County	Station	Altitude m	Annual Precipitation mm	Annual Temperature C°	Annual Rel. Air-humidity %	Rain factor	N-S-Quotient
Alabama	Jefferson	Birmingham	214	1342	17,44	71	77	312
Alabama	Mobile	Mobile	26	1589	19,44	79	82	451
Alabama	Montgomery	Montgomery	73	1317	18,61	72	71	295
Arizona	Navajo	Ft. Apache	1585	465	11,39	54	41	100
Arizona	Graham	Ft. Grant	1473	364	16,39	41	22	44
Arizona	Maricopa	Phoenix	307	191	20,83	43	9	18
Arizona	Pima	Tucson	738	298	19,33	41	15	30
Arizona	Yuma	Yuma	43	85	22,17	43,5	4	8
Arkansas	Sebastian	Ft. Smith	139	974	16,00	70	61	240
Arkansas	Pulaski	Little Rock	109	1225	16,67	71,5	73	305
Colorado	Pueblo	Pueblo	1428	294	10,89	51,5	27	63
Colorado	La Plata	Durango	1996	508	8,06	59,5	63	156
Colorado	Mesa	Gr. Junction	1403	214	11,22	51	19	43
Colorado	Montrose	Montrose	1771	246	9,00	48,5	27	55
Connecticut	Hartford	Hartford	48	1175	9,78	71,5	120	457
Connecticut	New Haven	New Haven	39	1163	9,94	73	117	472
Florida	Hills Borough	Tampa	31	1275	22,22	79	57	307
Florida	Palm Beach	Jupiter	6	1510	23,17	80,5	65	368
Florida	Monroe	Key West	5	947	24,94	77	39	175
Florida	Dade	Miami	25	1523	23,94	76,5	64	293
Florida	Duval	Jacksonville	68	1291	20,72	79,5	62	347
Florida	Escambia	Pensacola	46	1469	19,8	79,5	74	422
Georgia	Bibb	Macon	113	1140	17,83	72,5	64	273
Georgia	Richmond	Augusta	55	1181	17,89	74,5	66	304
Idaho	Nez	Lewiston	231	340	11,67	63	29	90
Idaho	Ada	Boise	840	349	10,56	56,5	33	85
Idaho	Bannock	Pocatello	1365	353	8,61	56	41	97

TABLE 1.—SUMMARY OF THE CLIMATOLOGICAL DATA FOR THE UNITED STATES—CONTINUED

State	County	Station	Altitude m	Annual Precipitation mm	Annual Temperature C°	Annual Rel. Air-humidity %	Rain factor	N-S-Quotient
Illinois	Peoria	Peoria	186	876	10,00	77	88	417
Illinois	Sangamon	Springfield	196	916	11,50	72	80	325
Illinois	Alexander	Cairo	108	1040	14,44	73,5	72	321
Illinois	Cook	Chicago	251	838	9,44	73,5	89	358
Indiana	Allen	Ft. Wayne	261	944	10,17	74	93	394
Indiana	Vanderburg	Evansville	131	1101	13,94	71,5	79	326
Indiana	Marion	Indianapolis	251	1027	11,56	71	89	350
Indiana	Vigo	Terre Haute	176	988	12,50	72	79	327
Iowa	Lee	Keokuk	187	856	11,28	74,5	79	349
Iowa	Woodberry	Sioux City	346	684	8,72	71,5	78	286
Iowa	Polk	Des Moines	262	816	9,67	71,5	84	320
Iowa	Floyd	Charles City	335	805	7,33	80	110	527
Iowa	Scott	Davenport	85	819	9,83	73	83	332
Iowa	Dubuque	Dubuque	213	848	8,83	75	96	401
Kansas	Cloud	Concordia	424	670	11,44	70	59	223
Kansas	Ford	Dodge City	765	510	12,39	66,5	41	142
Kansas	Sedwick	Wichita	420	766	13,11	68	58	213
Kentucky	Jefferson	Louisville	163	1181	13,33	68,5	88	330
Louisiana	Orleans	New Orleans	15	1448	20,67	78	70	361
Louisiana	Caddo	Shreveport	76	1094	18,72	72	58	242
Maine	Washington	East Port	23	1041	5,28	79	198	750
Maine	Cumberland	Portland	30	1072	7,94	74	135	520
Maryland	Baltimore	Baltimore	35	1084	12,94	69	84	316
Massachusetts	Suffolk	Boston	38	1111	9,67	72	115	446
Massachusetts	Nantucket	Nantucket	14	1000	9,56	83	105	666
Michigan	Delta	Escanaba	184	776	5,00	79	155	568
Michigan	Marquette	Marquette	224	825	5,11	75,5	161	512
Michigan	Chippewa	Sault St. Mary	187	769	4,11	80,5	187	651
Michigan	Ottawa	Gr. Haven	191	851	7,94	77	107	465
Michigan	Kent	Gr. Rapids	215	970	9,11	75	106	450
Michigan	Mason	Ludington	194	731	7,33	79	100	456
Minnesota	St. Louis	Duluth	344	735	3,83	77,4	192	542
Minnesota	Clay	Moorhead	285	600	4,39	79	137	457
Minnesota	Ramsey	St. Paul	287	696	6,83	71,5	102	329
Mississippi	Lauderdale	Meridian	114	1338	17,66	76	76	372
Mississippi	Warren	Vicksburg	75	1322	18,66	74	71	320
Missouri	Boone	Columbia	239	955	12,50	75	76	354
Missouri	Jackson	Kansas City	294	936	12,67	69	74	276
Missouri	St. Louis	St. Louis	172	1110	13,33	69,5	76	291
Missouri	Greene	Springfield	373	1069	13,11	73	81	352
Missouri	Buchanan	St. Joseph	295	829	12,22	70	68	261
Montana	Hill	Havre	764	344	5,17	71	67	180
Montana	Lewis and Clark	Helena	1253	340	6,39	59	53	116
Nebraska	Lincoln	North Platte	866	477	9,22	68,5	52	175
Nebraska	Cherry	Valentine	792	495	8,11	69,5	61	202
Nebraska	Douglas	Omaha	335	759	10,28	69	74	265
Nebraska	Lancaster	Lincoln	363	724	10,50	69,5	69	250
Nevada	Washoe	Reno	1381	212	9,67	53,4	22	51
Nevada	Nye	Tonopah	1856	138	9,94	45	14	28
Nevada	Humboldt	Winnemucca	1324	213	9,11	52,5	23	52

TABLE 1.—SUMMARY OF THE CLIMATOLOGICAL DATA FOR THE UNITED STATES—CONTINUED

State	County	Station	Altitude m	Annual Precipitation mm	Annual Temperature C°	Annual Rel. Air-humidity %	Rain factor	N-S-Quotient
New Jersey	Atlantic	Atlantic City	5	1029	11,22	79	92	494
New Jersey	Monmouth	Sandy Hook	7	1180	10,94	80	108	608
New Jersey	Mercer	Trenton	18	1240	12,00	72,5	103	432
New Mexico	Santa Fe	Santa Fe	2138	372	9,33	50,5	40	86
New York	Erie	Buffalo	183	931	8,28	75,5	113	466
New York	Monroe	Rochester	152	843	8,56	73	99	376
New York	Oswego	Oswego	102	926	7,78	77	119	512
New York	Onondago	Syracuse	182	881	8,17	73,5	108	411
New York	Albany	Albany	30	958	9,00	74,5	106	439
New York	New York	New York City	96	1071	11,17	71	96	268
North Carolina	Buncombe	Asheville	687	1012	12,67	76,5	80	396
N. Carolina	Mecklenbg.	Charlotte	237	1190	15,67	70	76	302
N. Carolina	Wake	Raleigh	119	1184	15,50	72	76	324
N. Carolina	Dare	Hatteras	3	1389	16,17	81	86	535
N. Dakota	Burleigh	Bismarck	509	434	4,56	71	95	238
N. Dakota	Williams	Williston	570	366	4,00	70	92	201
N. Dakota	Ramsey	Devils Lake	451	446	2,94	75,5	152	323
Oklahoma	Oklahoma	Oklahoma City	378	788	15,22	69,5	52	200
Ohio	Cuyahoga	Cleveland	232	869	9,56	73	91	362
Ohio	Erie	Sandusky	191	857	10,06	73,5	85	353
Ohio	Lucas	Toledo	234	806	9,83	73	82	330
Ohio	Hamilton	Cincinnati	191	1032	12,72	70	81	312
Ohio	Montgomery	Dayton	274	974	11,49	66,5	85	288
Ohio	Franklin	Columbus	280	928	11,22	72,5	83	340
Oregon	Baker	Baker	1058	311	7,44	62	42	107
Pennsylvania	Erie	Erie	218	963	9,28	74,5	104	434
Pennsylvania	Allegheny	Pittsburg	257	918	11,44	71	80	314
Pennsylvania	Dauphin	Harrisburg	110	1001	11,17	70	90	337
Pennsylvania	Lackawanna	Scranton	245	956	9,56	74	100	414
Rhode Island	New Port	Block Island	8	1066	9,67	82	110	660
Rhode Island	Providence	Providence	49	1122	9,67	72,5	116	458
S. Carolina	Richland	Columbia	107	1117	17,44	70,5	64	257
S. Carolina	Greenville	Greenville	317	1320	15,06	72,5	87	378
S. Carolina	Charleston	Charleston	15	1214	18,67	78	65	347
S. Dakota	Pennington	Rapid City	991	450	7,89	59	57	138
S. Dakota	Hughes	Pierre	479	432	8,11	65,5	53	155
Tennessee	Shelby	Memphis	125	1240	16,44	71,5	75	312
Tennessee	Davidson	Nashville	199	1217	15,17	71	80	327
Tennessee	Hamilton	Chattanooga	232	1302	15,78	73	83	365
Tennessee	Knox	Knoxville	304	1231	14,50	73,5	85	379
Texas	Taylor	Abilene	53	617	17,78	62	35	108
Texas	Potter	Amarillo	1119	529	13,22	61,5	40	122
Texas	Tarrant	Forth Worth	204	848	18,39	66,5	46	161
Texas	Williamson	Taylor	178	790	19,33	72	41	170
Texas	Dallas	Dallas	142	964	18,33	67	53	186
Texas	Anderson	Palestine	155	1035	18,83	74	55	247
Texas	Nueces	Corp. Christi	6	631	21,33	81,5	30	181
Texas	Valverde	Del Rio	289	484	20,61	65	24	77
Texas	Galveston	Galveston	21	1174	20,94	80,5	56	327
Texas	Harris	Houston	42	1201	20,56	71,5	58	234
Texas	Jefferson	Port Arthur	10	1440	20,00	82	72	461

TABLE 1.—SUMMARY OF THE CLIMATOLOGICAL DATA FOR THE UNITED STATES—CONTINUED

State	County	Station	Altitude m	Annual Precipitation mm	Annual Temperature C°	Annual Rel. Air-humidity %	Rain factcr	N-S-Quotient
Texas	Bexar	San Antonio	214	704	20,50	67,5	34	120
Utah	Iron	Modena	1670	284	8,83	51,9	32	70
Utah	Salt Lake	Salt Lake City	1344	412	10,89	52,4	38	89
Virginia	Wythe	Wytheville	699	1026	11,22	79	92	492
Vermont	Chittenden	Burlington	123	825	7,22	71	114	377
Vermont	Washington	Northfield	267	840	5,00	79	168	614
Washington	Spokane	Spokane	593	422	9,00	63,5	47	135
Washington	Walla Walla	Walla Walla	305	436	11,89	63	37	114
W. Virginia	Randolph	Elkins	598	1196	10,06	79,5	119	635
W. Virginia	Wood	Parkersburg	194	994	12,22	75	81	376
Wiscensin	Broun	Green Bay	189	775	6,67	70,5	116	360
Wisconsin	Dane	Madison	297	792	7,61	74,5	104	399
Wisconsin	Milwaukee	Milwaukee	208	787	7,67	75	102	403
Wyoming	Yellowstone	Yellowstone Park	1890	465	3,72	65	125	223
Wyoming	Laramie	Cheyenne	1856	355	7,00	57	51	110
Wyoming	Freemont	Lander	1637	344	5,78	59	59	122
Wyoming	Sheridan	Sheridan	1155	367	6,17	67,5	60	160

Calculation of N. S. Quotient

The vapor tension which corresponds to the annual temperature of any meterological station can be found in physico-chemical handbooks or in Smithsonian Meteorological Tables. Example: The annual temperature of Sheridan (Wyoming) is 6.17°C. The vapor tension for this particular temperature is 7.06 mm Hg according to Smithsonian Metercleogical Tables. The absolute saturation deficit for Sheridan is obtained by multiplying the vapor tension with the relative saturation deficit in per cent. The latter term is cbtained by subtracting the relative air humidity figure frcm 100%. Example: The relative air humidity for Sheridan is 67.5%. The relative saturation deficit is therefore, 100%−67.5%=32.5%. The absolute saturation deficit is found by multiplication: 32.5% times 7.06 gives 2.29 mm Hg. The N. S. Quotient is, by definition, annual precipitation: abs-saturation deficit, which is for Sheridan $\frac{367}{2.29} = 160$ N. S. Q. (All calculation with slide rule).

THE NITROGEN AND ORGANIC MATTER-TEMPERATURE RELATION

The nitrogen-temperature relation is conveniently written in the following form:

$$N = f\ (\text{Temperature})_H \qquad \text{(IV)}$$

where the subscript H denotes that the humidity factor is kept constant; in other words, the correlation between nitrogen and temperature is investigated only for those soils which lie in regions of equal precipitation-evaporation ratios [20, 21, 26]. After the mathematical form of this relation is known, its differentiation will furnish the required partial derivative $(\partial N/\partial T)_H$.

Historical

Few investigators have published definite statements concerning *functional* relationships between climate and soil nitrogen or soil organic matter. Of course, numerous scientists have assumed a climatic influence and supported their views with more or less convincing figures, obtained mostly from limited districts. H. B. de Saussure, father of the famous agricultural chemist, suggested as early as 1796 that the organic matter content of the soil is linked up with climate.[62] It is interesting to note that scientists who are working in regions of extreme climatic conditions, for instance in semi-deserts[66], tropics[48,63], the frigid zones and high altitudes[19,24] are particularly interested in quantitative soil organic matter relationships, since in those regions organic matter occurs either in excessive or deficient amounts, thus attracting particular attention.

Observations in the tropics (Java and Sumatra) led E. C. J. Mohr[48,63] to make the following general statement: "In well aerated soils of the humid, warm tropics, with average temperatures of 25°C and higher, humus cannot maintain itself, nor can it accumulate." On the other hand, it was found by the author[19,24] that in high altitudes, where the annual temperature is around or below zero centigrade the soils contain on the average as much as 20-40 per cent organic matter, in spite of the meagre grass vegetation. DeTurk[7], summarizing a nitrogen survey of Illinois soils, expresses the idea that the low nitrogen content of the soils in the southern part of the state is due to the more favorable conditions for decomposition, such as higher temperature and rainfall. Attention should also be called to R. Lang's[33] deductions, although no data verifying his conclusions are given.

Theoretical Considerations

Nitrogen losses from the soil—in gaseous form and through leaching—result primarily from the microbiological decomposition process of organic matter. The biological activities follow, in a general way, the rule of Van't Hoff[6,71] which states that the velocity of many chemical reactions increases two to three times for each 10°C. rise in temperature, other conditions being constant. It has been found that this rule holds for lower organisms for temperatures up to 20-30°C.[4,32,56,87]. At higher temperatures the rate of change begins to decrease, becomes zero and then negative. Wollny's[87] curves of the CO_2-production from soils, and the denitrification and ammonification curves of Panganiban[56] which are shown in Figure 5, illustrate the intensity of the decomposition of organic matter with respect to temperature.

Assuming a *simple*, symmetrical S-shaped curve (Figure 5) for the trend of the decomposition process as influenced by moderate temperatures leads to the following expression for the rate of increase under constant moisture conditions:

$$\frac{dn}{dT} = k'n(a-n) \qquad \text{(V)}$$

where n, means nitrogen liberated, a, total amount of nitrogen present at the

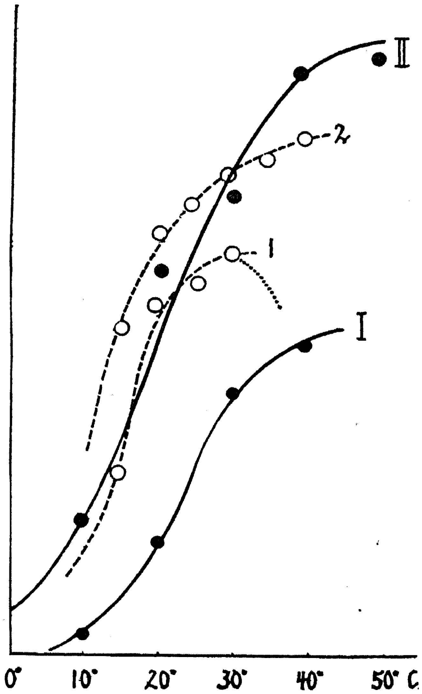

Fig. 5.—Effect of temperature on microbiological activity. I, II: CO_2-Production (Wollny). 1, 2: transformation of nitrogen (Panganiban).

beginning of the decomposition process, T, temperature, and k' a constant. This constant k' and all the following constants in this paper are, of course, not absolute natural constants (like the velocity of light for instance), but are apt to vary under different experimental conditions. Since the amount of nitrogen or organic material remaining in the soil decreases at the same rate as the decomposition and liberation of the compounds increases, we can write

$$-\frac{dN}{dT}=\frac{dn}{dT} \qquad \text{(VI)}$$

where N represents the amount of nitrogen left in the soil. But N is also equal to $(a-n)$, by definition, and similarly $n=a-N$. Hence

$$-\frac{dN}{dT}=k'N(a-N) \qquad \text{(VII)}$$

represents the expression for the rate of change of the undecomposed nitrogen compounds with respect to temperature. Transforming equation (VII) gives

$$k'dT=-\frac{dN}{N(a-N)} \qquad \text{or} \qquad \text{(VIII)}$$

$$-k'T=\int\frac{dN}{N(a-N)} \qquad \text{(IX)}$$

which can be integrated by resolution into partial fractions. Thus:

$$-k'T=\frac{1}{a}\log_e\frac{N}{a-N}+c \qquad \text{(X)}$$

or transformed into an exponential function:

$$N=\frac{a}{1+Ce^{kT}} \qquad \text{(XI)}$$

where $k=ak'$ and $C=e^{-ac}$, N represents the nitrogen content of the soil, a, the original nitrogen content before decomposition started, T, temperature, C, k, are constants. Equation XI which has been developed on mere theoretical reasoning and which might be considered a working hypothesis leads to the following conclusions:

a. Within regions of equal moisture conditions and vegetation (constant "a"), the nitrogen content of the soil decreases from north to south (increasing temperature).

b. The decrease of soil nitrogen with respect to temperature is exponential.

Some scientists[88] maintain the viewpoint that decomposition of organic matter can take place without participation of micro-organisms. It is worth while to point out in this connection that the mode of treatment of the present study is a physico-chemical one, resembling thermodynamical reasoning in that the soil organic matter climate system is treated as a whole and no attempt is made to deal with the actual mechanism of the decomposition process of organic matter itself. Consequently the conclusions arrived at are general and will not be altered by changes in views regarding decomposition of soil organic matter.

Experimental Nitrogen Temperature Relations

In order to study the variation of soil nitrogen with temperature, the moisture conditions must remain approximately constant. Regions of similar humidity factors were selected according to the N. S. Q. map on page 8. A summary of the various moisture areas and their topographical, vegetational, and textural characteristics is given in Table 2.

TABLE 2.—CHARACTERISTICS OF THE NITROGEN AND ORGANIC MATTER TEMPERATURE CURVES STUDIED

No. of Curve	Moisture conditions		Topography	Vegetation	Texture	Locality (States)
	Region	N. S. Q.				
No. 1	Semi-arid	125 - 250	Mainly upland	Grassland	Various	Canada to Texas
No. 2	Semi-humid	280 - 380	Upland	Prairie and some timber	Loams and silt loams	Canada to Louisiana
No. 3	Semi-humid	280 - 380	Terrace	Timber	Silt loams	Iowa to Arkansas
No. 4	Semi-humid	280 - 380	Bottom	Timber	Silt loams	Iowa to Arkansas
No. 5	Humid	300 - 420	Upland	Prairie	Silt loams	Wisconsin to Mississippi
No. 6	Humid	300 - 420	Upland	Timber	Silt loams	Wisconsin to Mississipi
No. 7	Semi-humid	280 - 380	Flat Upland	Prairie	Silt loam	Missouri
No. 8	Humid	300 - 450	Upland	Timber	Loams and sandy loams	New York to Florida

A total of eight nitrogen and organic matter-temperature relationships have been established, including upland, terrace, and bottom land soils, of both prairie and timbered districts. As to texture, mostly loams, silt loams, and sandy loams, being the most common soil textures in the United States, were investigated.

The underlying principle adopted in this study for the collection of nitrogen figures might be called a "random selection of equal soil areas" in that the average nitrogen content of the soils of equal areas which are scattered all over the selected region is being determined. For practical reasons the average nitrogen or humus content of a county area has been chosen as a comparable unit (See Figure 6). All nitrogen analyses of a county were arranged according to topography, vegetation, and texture, and their re-

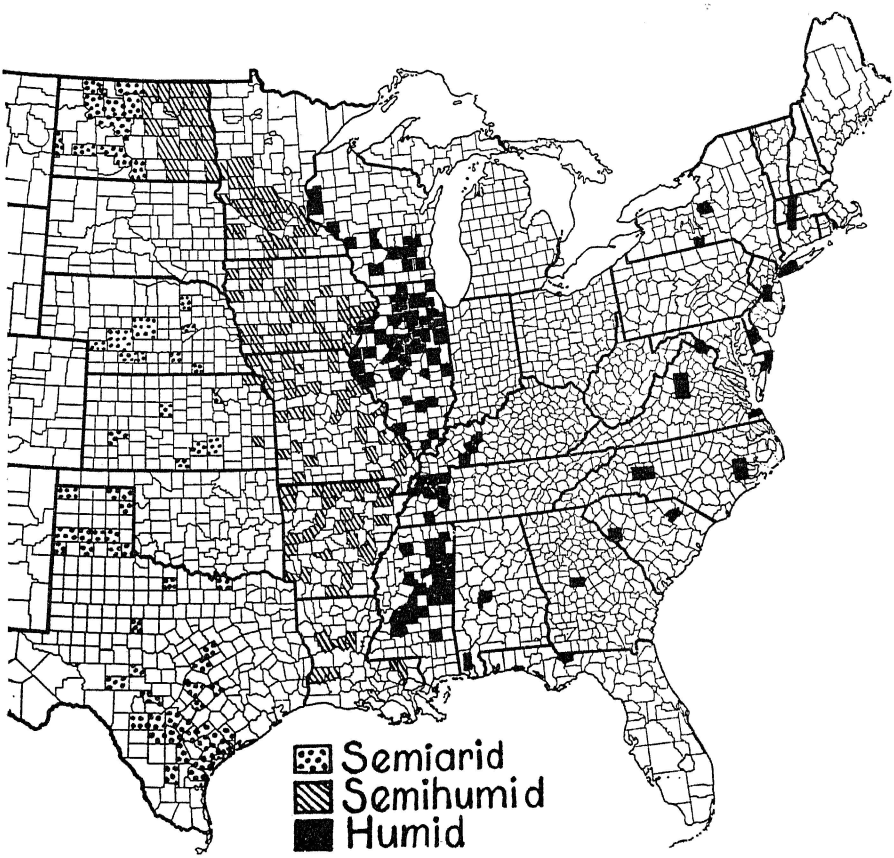

Fig. 6. Location of counties investigated for the study of the nitrogen and organic matter temperature relationship.

spective averages (based, if possible, on the area of the various soil types) were tabulated with the mean annual temperature and annual humidity factor of the county (compare examples in Tables 3 and 4). Those comparable units were then plotted either directly or after being assembled in temperature classes in a coordinative system with temperature as abscissa and nitrogen or organic matter values as ordinate. In most cases the curves were smoothed according to the method of least squares, using the reciprocal mean errors as weights. The constant "a" was found by tryouts, and k was then algebraically computed. All counties investigated are shown in Figure 6.

TABLE 3.—ILLUSTRATION OF THE METHOD OF CALCULATING THE AVERAGE NITROGEN CONTENT OF THE SOILS OF A COUNTY

Black Hawk County, Iowa. Annual Temperature 46.6°F. Annual Humidity factor N. S. Q. about 368. Terrace soils.

Soil Type	Per Cent of County Area	N	Area X N	Average N
Waukesha silt loam	3.2	*Per Cent* 0.195	0.6240	*Per Cent* 0.7831 / 3.9
Bremer silt loam	0.6	0.242	0.1452	
Calhoun silt loam	0.1	0.139	0.0139	0.201 %N
Total	3.9		0.7831	County value or comparable unit.

TABLE 4.—ILLUSTRATION OF THE METHOD OF CALCULATING THE AVERAGE ORGANIC MATTER CONTENT OF THE SOILS OF A COUNTY

Perry County, Alabama. Annual Temperature 64.5°F. Annual Humidity factor N. S. Q. about 310. Upland soils.

Soil types (Coastal Plain Soils)	Per cent of county area	Analyses of organic matter content		Area X Average	Average organic matter content of county per cent
		Single values per cent	Average per cent		
Orangeburg sandy loam	40.2	0.38, 0.70, 0.64, 0.67	0.57	40.2X0.57=22.91	27.41 / 43.2
Sassafras sandy loam	3.0	2.01, 1.00.	1.50	3.0X1.50= 4.50	
	43.2			27.41	0.63 %O.M.

This method of calculation might be called an arithmetical "short cut" of the following mode of reasoning. In calculating the average organic matter content of a county, not only the organic matter content of the various soil types, but also their area has been taken into consideration. Thus, in the above example the county organic matter content, if based solely on the average analyses of the two soil types, is $\frac{0.57+1.50}{2}$ 1.035 per cent, which is not a fair value, because the abnormally high organic matter value of the unimportant soil type Sassafras sandy loam receives too great a share in forming the county average. This error is corrected by using the area of the soil types as "weight". In the above case, the area of Perry County is 487,744 acres. The Orangeburg sandy loam occupies 40.2 per cent or 196,073 acres, the Sassafras sandy loam 3.0 per cent of 14,632 acres. The organic matter percentage multiplied by 20,000 gives the organic matter content in pounds per acre, 6⅝ inches deep (2 million pounds of soil), which is 11,400 pounds for the Orangeburg sandy loam and 30,000 pounds for the Sassafras sandy loam. Multiplying pounds of organic matter per acre with the number of acres gives the total amount of organic matter present in the entire area of the respective soil types. Hence, for Orangeburg sandy loam: 11,400 . 196,073=2.235.10^9 pounds and for the Sassafras sandy loam: 30,000 . 14,632=0.439.10^9 pounds. The 210,705 acres (both soil types together) contain, therefore, 2.674.10^9 pounds of organic matter or one acre contains 2.674.10^9 divided by 210,705=12,682 pounds per acre. Dividing this value by 20,000 converts the pound per acre value into the percentage figure, which gives 0.63 per cent O. M.

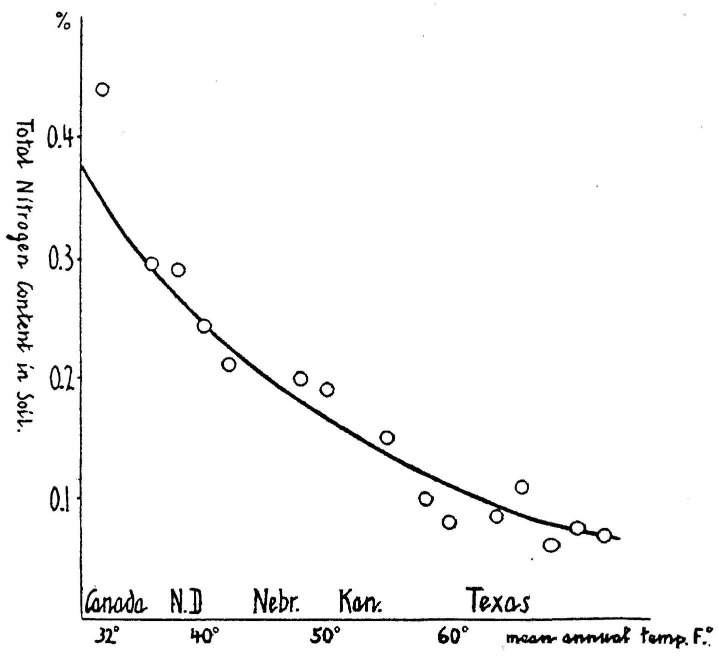

Fig. 7. Showing average total nitrogen content of the soil as related to the mean annual temperature in the semi-arid region.

Semi-arid Region, (Curve 1, Figure 7)

In the semi-arid region (N. S. Q. 175-250), which includes eastern Alberta[65], southwestern Saskatchewan[5,27], western North[53] and South Dakota, eastern Montana, western and central Nebraska[51], western and central Kansas[70], the Texas Panhandle[72], Oklahoma and central and south central Texas[72], 348 nitrogen values were available from bulletins of the various experiment stations.

For this region the plotting of the averages of the nitrogen values against their temperatures and the calculation of the constants gives the following special equation:

$$N_{\text{SEMI-ARID}} = \frac{1.70}{1+e^{0.045(T-1.50)}} \qquad \text{(XII)}$$

in which N represents the average total nitrogen content of the soil in percentage, T the mean annual temperature in degrees F. The curve is given in Figure 7, and calculated and observed values in Table 5. On account of the limited number of data available, no separation of texture and topography was made. The natural vegetation of the entire region is grass.[64] The forest districts of central Texas were omitted.

TABLE 5.—THE NITROGEN-TEMPERATURE RELATION IN THE SEMI-ARID REGION.[1]

Mean annual temperature °F.	Mean annual temperature °C.	State	Humidity factors 125-250: Number of counties (units)	Number of nitrogen values	Average nitrogen content %	Calculated value	Deviation
32[2]	0.00	Canada	—	10	*0.44*[3]	0.344	+0.096
36	2.22	Canada / N. Dakota	5	30	*0.295*±0.050	0.297	−0.002
38	3.33	N. Dakota	4	5	*0.291*±0.032	0.276	+0.015
40	4.44	N. Dakota	5	12	*0.244*±0.015	0.256	−0.012
42	5.56	N. Dakota	1	1	*0.21*[3]	0.237	−0.027
48	8.89	Nebraska	2	17	*0.199*±0.0077	0.187	+0.012
50	10.00	Nebraska	7	28	*0.192*±0.012	0.172	+0.020
55	12.78	Kansas	6	47	*0.152*±0.022	0.140	+0.012
58	14.44	Texas	12	32	*0.100*±0.0065	0.124	−0.024
60	15.56	Texas	3	8	*0.081*±0.022	0.114	−0.033
64	17.78	Texas	3	27	*0.085*±0.012	0.096	−0.011
66	18.89	Texas	2	40	*0.112*±0.010	0.088	+0.024
68	20.00	Texas	3	25	*0.063*±0.0091	0.081	−0.018
70	21.11	Texas	13	48	*0.075*±0.0076	0.075	−0.000
72	22.22	Texas	5	18	*0.075*±0.0040	0.068	+0.007
Temperature range 40°	22.22°	Total 5	Total. 71	Total 348	Range 0.44% to 0.063%	a=1.70 c=1.00 k=0.045	

[1]Detailed data from which Tables 1 and 2 were summarized may be obtained from the author. [2]Temperature estimated. [3]Not used in calculating the constants.

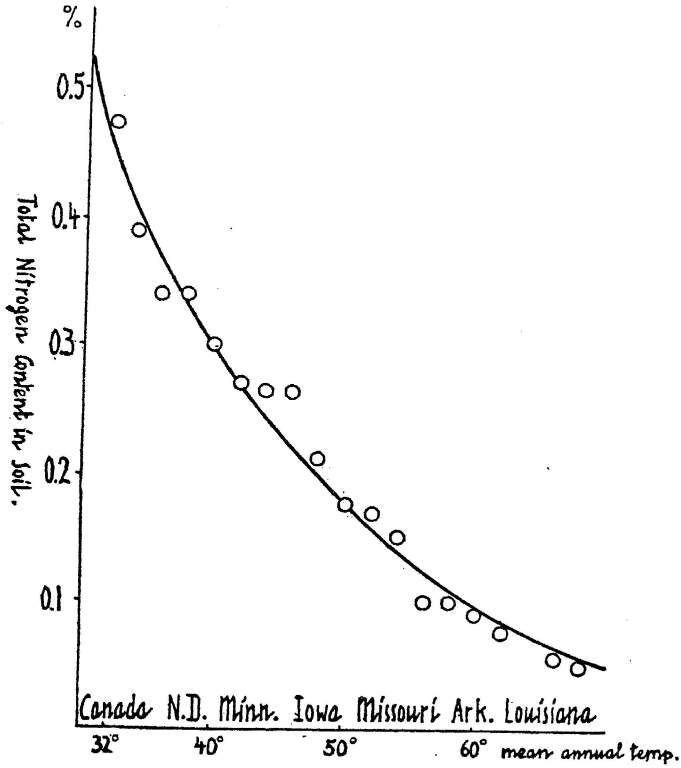

Fig. 8. Showing average total nitrogen conten. of the soil as related to the mean annual temperature in the semi-humid region.

Semi-humid Upland Soils, (Curve No. 2, Figure 8)

From the semi-humid region (N. S. Q. 280-380) which includes eastern Saskatchewan[5 27], southwestern Manitoba, eastern North[53] and South Dakota, southwestern Minnesota[43], Iowa[17], eastern Kansas[70], Missouri[45], Arkansas[52], and Louisiana[81], 475 nitrogen values were assembled. For this particular region the equation has the form

$$N_{\text{Semi-humid}} = \frac{1.55}{1+e^{0.065(T-18.5)}} \qquad \text{(XIII)}$$

The curve is shown in Figure 8 and the agreement of the experimental data with the calculated values in Table 6. The abundance of data permitted the selection of the values of only loam and silt loam soils, thus limiting the variation in texture. In addition, all river bottom soils, such as the Wabash series, for example, were omitted and only the predominating upland soil types of the county as shown by the soil maps were used.

TABLE 6.—THE NITROGEN-TEMPERATURE RELATION IN THE SEMI-HUMID REGION
Humidity factors 280-380

Mean annual temperature °F.	Mean annual temperature °C.	State	Number of counties (units)	Number of nitrogen values	Average nitrogen content %	Calculated value	Deviation
32[1]	0.00	Canada	—	16	*0.475*[2]	0.455	+0.020
34	1.11	Canada	1	17	*0.393*±0.023	0.414	−0.021
36	2.22	N. Dakota	7	20	*0.341*±0.017	0.376	−0.035
38	3.33	N. Dakota	4	6	*0.341*±0.083[2]	0.340	+0.001
40	4.44	N. Dakota	10	32	*0.295*±0.017	0.307	−0.012
42	5.56	Minnesota	7	17	*0.273*±0.018	0.276	+0.003
44	6.67	Minnesota	16	44	*0.266*±0.012	0.248	+0.018
46	7.78	Minnesota, Iowa	11	23	*0.266*±0.014	0.222	+0.044
48	8.89	Iowa	9	26	*0.210*±0.014	0.198	−0.012
50	10.00	Iowa, Missouri	21	54	*0.172*±0.0050	0.177	−0.005
52	11.11	Iowa, Missouri	11	60	*0.168*±0.0070	0.160	+0.008
54	12.22	Missouri, Kansas	10	56	*0.150*±0.012	0.140	+0.010
56	13.33	Missouri	13	56	*0.101*±0.0094	0.124	−0.023
58	14.44	Missouri, Arkansas	9	20	*0.098*±0.0095	0.110	−0.012
60	15.56	Arkansas	8	8	*0.091*±0.0081	0.098	−0.007
62	16.67	Arkansas	3	3	*0.078*±0.0057	0.086	−0.008
66	18.89	Louisiana	3	6	*0.056*±0.0015	0.067	−0.011
68	20.00	Louisiana	4	11	*0.050*±0.0064	0.059	−0.009
Temperature range 36°	20.00°	Total 9	Total 147	Total 475	Range 0.475% to 0.050%	a=1.55 C=1.00 k=0.065	

[1]Temperature estimated.
[2]Not used in calculating the constants.

The natural vegetation on the soils represented by the upper part of the curve for this region is mainly prairie grass[64], and in order to eliminate variable vegetation as much as possible, only this part of the curve was used in calculating the constants. The part of the curve below 56°F. represents soils from southern Missouri, Arkansas, and Louisiana with original forest vegetation, mainly of oaks.

Semi-humid Terrace Soils, (Curve No. 3, Figure 10)

The terraces, often styled "second bottoms" and "bench" lands, include old flood plains which now stand largely above the influence of overflow, the streams having cut their channels to lower levels[36]. The original vegetation consists mainly of timber. Figure 9 illustrates the relative position of flood plain, terrace and upland in Missouri.

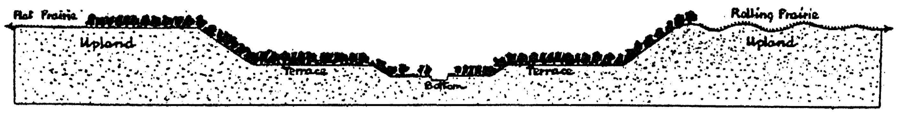

Fig. 9. Schematic arrangement of flood plain, terrace, and upland.

About twenty-two different soil series have been included in the study of this nitrogen-temperature relation, representing the states of Iowa[17], Missouri[45] and Arkansas.[52]

The computed equation for terrace soils has the form

$$\frac{N}{\text{Terrace}} = \frac{1.80}{1+e^{0.069(T-18.80)}} \qquad \text{(XIV)}$$

where N represents average nitrogen content of the soil in percentage and T the mean annual temperature F.°. Observed and calculated values are summarized in Table 7 and the graph is given in Figure 10. Also for terrace soils the nitrogen-temperature relation is remarkably exponential. One wonders whether the uniformity in the distribution of nitrogen is entirely due to temperature or whether the nature of terrace soils consisting of outwash of surrounding upland soils which themselves show the nitrogen-temperature relation did not help to determine the relationship.

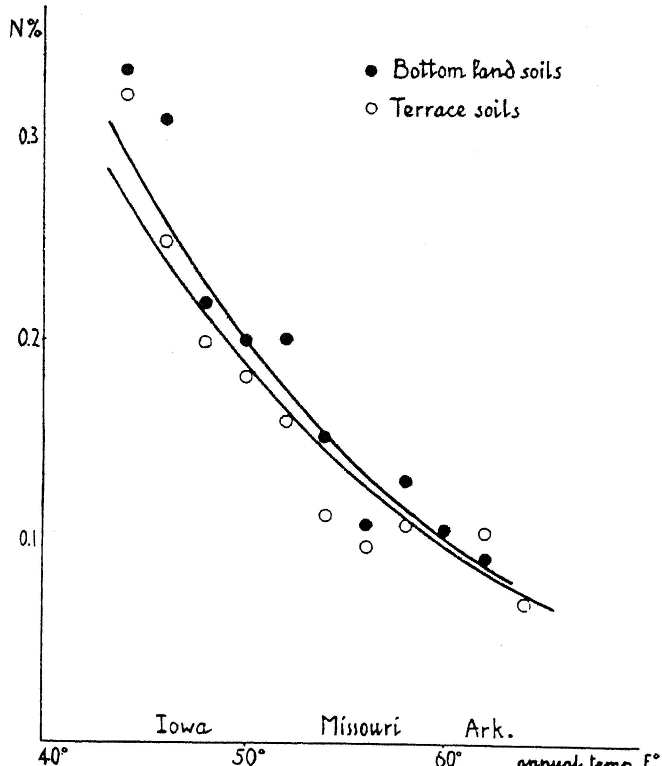

Fig. 10. Nitrogen-temperature relation in semi-humid bottom land soils (upper curve) and terrace soils (lower curve) for silt loams.

TABLE 7.—NITROGEN-TEMPERATURE RELATION IN SEMI-HUMID TERRACE SOILS (SILT LOAMS)
Humidity factors 280-380

Mean annual temperature °F.	Mean annual temperature °C.	State	Number of counties (units)	Number of nitrogen values	Average nitrogen content per cent	Calculated value	Deviation
44.0	6.67	Iowa	7	9	*0.322*±0.056	0.269	+0.053
46.0	7.78	Iowa	2	4	*0.249*±0.049	0.239	+0.010
48.0	8.89	Iowa	17	41	*0.198*±0.007	0.212	−0.014
50.0	10.00	Iowa, Missouri	9	20	*0.181*∓0.011	0.187	−0.006
52.0	11.11	Iowa, Missouri	5	7	*0.160*±0.020	0.165	−0.005
54.0	12.22	Missouri	5	8	*0.113*±0.013	0.146	−0.033
56.0	13.33	Missouri	7	17	*0.095*±0.015	0.128	−0.033
58.0	14.14	Missouri	9	8	*0.109*±0.003	0.113	−0.004
62.0	16.67	Arkansas	4	4	*0.105*±0.009	0.087	+0.018
64.0	17.78	Arkansas	2	2	*0.072*±*0*.003	0.076	−0.004
Temperature range 20.0	11.11	Total 3	Total 61	Total 120	Nitrogen range 0.322 to 0.072%	Constants a=1.80 k=0.069	

Semi-humid First Bottom Land Soils, (Curve No. 4, Figure 10)

The first bottom lands occur along the banks of the streams in continuous and interrupted strips varying from a few feet wide along the minor drainage courses to broad bottoms several miles wide. They are subject to submergence by overflow waters. The surface is dominantly flat and level, and the natural vegetation consists predominantly of timber with some meadows and swamps[36].

Bottom land soils, including twenty-one series representing the states of Iowa[17], Missouri[45], and Arkansas[52], were investigated. Numerical information of the results obtained is given in Table 8, graphic representation in Figure 10. The equation has the form:

$$\frac{N}{\text{Bottom Land}} = \frac{1.60}{1+e^{0.075(T-24.00)}} \qquad \text{(XV)}$$

where N and T have the usual meaning.

The curves of bottom land and terrace soils run nearly parallel, the former lying above the latter. The difference, however, is not important enough to indicate that bottom silt loams contain on the average much more nitrogen than the terrace silt loams. The same similarity is observed for the carbon-nitrogen ratio (Table 9).

TABLE 8.—NITROGEN-TEMPERATURE RELATION IN SEMI-HUMID BOTTOM LAND SOILS (SILT LOAMS)
Humidity factors 280-380

Mean annual temperature °F.	Mean annual temperature °C.	State	Number of counties (units)	Number of nitrogen values	Average nitrogen content	Calculated value	Deviation
					per cent		
44.0	6.67	Iowa	7	9	*0.327*±0.040	0.292	+0.035
46.0	7.78	Iowa	2	2	*0.310*±0.019	0.258	+*0.052*
48.0	8.89	Iowa	14	20	*0.218*±0.020	0.227	−0.009
50.0	10.00	Iowa, Missouri	9	16	*0.200*±0.012	0.199	+0.001
52.0	11.11	Iowa, Missouri	9	22	*0.202*±0.016	0.175	+0.027
54.0	12.22	Missouri	12	24	*0.150*±0.010	0.152	−0.002
56.0	13.33	Missouri	10	16	*0.109*±0.008	0.133	−0.024
58.0	14.44	Missouri	4	11	*0.131*±0.010	0.116	+0.015
60.0	15.56	Arkansas	3	7	*0.106*±0.010	0.101	+0.005
62.0	16.67	Arkansas	2	6	*0.092*±0.015	0.087	+0.005
Temperature range 18.0	10.00	Total 3	Total 73	Total 133	Nitrogen range 0.327 to 0.092%	Constants *a*=1.60 *k*=0.075	

TABLE 9.—CARBON-NITROGEN RATIO IN TERRACE AND BOTTOM SOILS OF IOWA

Temperature °F.	Temperature °C.	Terrace soils (31 values)	Bottom soils (31 values)
44.0	6.67	11.97±0.286	12.60±0.305
46.0	7.78	11.90±0.200	11.87±0.437
48.0	8.89	12.06±0.240	12.33±0.348
50.0	10.00	12.40±0.235	11.88±0.463
Average		12.33±0.484	12.17±0.787

Humid Prairie and Timber Soils, (Curves No. 5 and 6, Figure 11)

East of the Mississippi River the precipitation-evaporation ratio slowly increases. The semi-humid region grades into the humid region. The part of the humid region investigated includes southern Wisconsin[85], Illinois[16], western Kentucky[3], western Tennessee[49], and Mississippi[15]. The natural

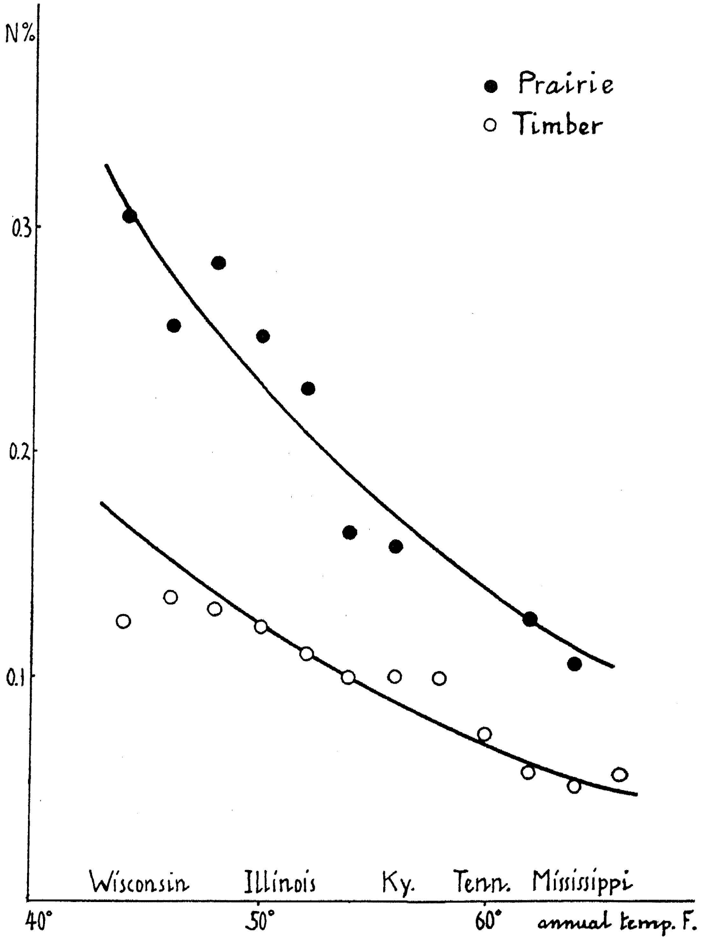

Fig. 11.—Nitrogen-temperature relation in humid prairie (upper curve) and humid timber soils (lower curve) for silt loams.

vegetation consists partly of timber and partly of prairie. Only upland soils, particularly silt loams, were studied. Fortunately the soil surveys of Wisconsin, Illinois and Mississippi separate clearly the prairie and timber soils in their work, thus permitting the construction of two distinct curves for the entire region. Figure 11 and Tables 10 and 11 give the essential features.

TABLE 10.—NITROGEN-TEMPERATURE RELATION IN HUMID PRAIRIE SOILS (SILT LOAMS)

Mean annual temperature °F.	Mean annual temperature °C.	State	Number of counties (units)	Number of nitrogen values	Average nitrogen content per cent	Calculated value	Deviation
44.0	6.67	Wisconsin	2	6	*0.304*±0.028	0.305	−0.001
46.0	7.78	Wisconsin, Illinois	4	11	*0.256*±0.011	0.287	−0.031
48.0	8.89	Illinois	9	9	*0.285*±0.016	0.254	+0.031
50.0	10.00	Illinois	11	12	*0.252*±0.009	0.231	+0.021
52.0	11.11	Illinois	8	10	*0.228*±0.008	0.210	+0.018
54.0	12.22	Illinois	5	7	*0.164*±0.012	0.190	−0.026
56.0	13.33	Illinois	2	3	*0.158*±0.020	0.172	−0.014
62.0	16.67	Mississippi	5	16	*0.125*±0.016	0.127	−0.002
64.0	17.78	Mississippi	6	19	*0.105*±0.008	0.114	−0.009
Temperature range 20.0	11.11	Total 4	Total 52	Total 93	Nitrogen range 0.304 to 0.105%	Constants $a=1.60$ $k=0.056$	

TABLE 11.—NITROGEN-TEMPERATURE RELATION IN HUMID TIMBER SOILS (SILT LOAMS)

Mean annual temperature °F.	Mean annual temperature °C.	State	Number of counties (units)	Number of nitrogen values	Average nitrogen content per cent	Calculated value	Deviation
44.0	6.67	Wisconsin	3	13	*0.124*±0.010	0.168	−0.044
46.0	7.78	Wisconsin, Illinois	7	33	*0.135*±0.008	0.151	−0.016
48.0	8.89	Illinois	9	9	*0.130*±0.007	0.136	−0.006
50.0	10.00	Illinois	10	14	*0.124*±0.005	0.122	+0.002
52.0	11.11	Illinois	8	12	*0.110*±0.013	0.110	+0.000
54.0	12.22	Illinois	5	10	*0.099*±0.007	0.098	+0.001
56.0	13.33	Illinois, Kentucky	4	9	*0.102*±0.007	0.088	+0.014
58.0	14.44	Illinois, Kentucky, Tennessee	9	15	*0.100*±*0.009*	0.080	+0.020
60.0	15.56	Tennessee, Mississippi	5	14	*0.074*±0.008	0.069	+0.005
62.0	16.67	Mississippi	5	12	*0.057*±0.006	0.062	−0.005
64.0	17.78	Mississippi	7	20	*0.051*±0.003	0.055	−0.004
66.0	18.89	Mississippi	3	20	*0.056*±0.012	0.051	+0.005
Temperature range 22.0	12.22	Total 5	Total 75	Total 185	Nitrogen range 0.135 to 0.051%	Constants $a=1.00$ $k=0.062$	

The equations have the form:

$$\frac{N}{\text{Humid Prairie}} = \frac{1.60}{1+\epsilon^{0.056(T-58.20)}} \qquad \text{(XVI)}$$

$$\frac{N}{\text{Humid Timber}} = \frac{1.00}{1+e^{0.062(T-18.20)}} \qquad \text{(XVII)}$$

where N and T have the ordinary meaning.

The nitrogen content of both prairie and timber soils decreases exponentially with increasing temperature, although this is less pronounced in the case of the timber curve. The well-known superiority of the prairie soils over the timber soils in nitrogen content is remarkably shown in the entire region. The exact cause of this difference in nitrogen cannot be determined from the present data, since it is not known how much organic matter is produced by the forests of that region. The constant "a" in the equation (1.60, 1.00) which stands for the nitrogen content of the vegetation might be partly responsible. The average carbon-nitrogen ration is the same for both groups, as illustrated in Table 12.

TABLE 12.—CARBON-NITROGEN RATIO IN PRAIRIE AND TIMBER SOILS OF ILLINOIS (SILT LOAMS)

Temperature		Prairie soils (33 values)	Timber soils (32 values)
°F.	°C.		
48.0	8.89	11.36±0.315	11.56±0.581
50.0	10.00	12.33±0.207	11.21±0.258
52.0	11.11	11.79±0.229	11.03±0.272
54.0	12.22	10.83±0.693	11.10±0.203
Average		11.58±0.821	11.23±0.721

Nitrogen-Temperature Relation in the Level Prairie Soils of Missouri, (Curve No. 7, Figure 13)

The question may arise as to how large an area must be considered in order to find a nitrogen-temperature relationship. Generally it can be answered that the narrower the annual isotherms run, the smaller the area that may lend itself to such studies.

To give a definite answer, the flat prairie soils of Missouri were selected, because they offer a minimum of variation in soil texture, profile, topography, drainage, vegetation, and humidity.[39] The location of these prairie soils, including the soil types Putnam silt loam, Oswego silt loam, and Cherokee silt loam, is shown in Figure 12. The area covered has a length from north to south (southern Iowa to southern Missouri) of about 280 miles and an annual temperature range of about 7°F. or about 4°C. Climatic data of surrounding stations are given in Table 13. The average nitrogen values for each county are given in Table 14, the graph in Figure 13. With so narrow a temperature range, it is safe to assume that the nitrogen temperature relation can be represented by a straight line. After forming temperature classes with intervals 2°F. and nitrogen classes with intervals 0.02%N, a correlation coefficient (r) = −0.77 can be computed. It expresses the degree to which the two variables, nitrogen and temperature, tend to be associated. Perfect correlation would give a value of −1.00; no correlation, a value of zero.

With the aid of the correlation coefficient the line of best fit can easily be calculated. It has the form:

$$N = -0.0131\, T_{49^\circ}^{57^\circ} + 0.8522 \qquad \text{(XVIII)}$$

where N represents the average nitrogen content of the soil in percentage and T the mean annual temperature in °F. (49°F.−57°F.).

Summarizing we may state that the N-T relation can be clearly demonstrated within a region as small as that covered by the flat prairie soils of Missouri.

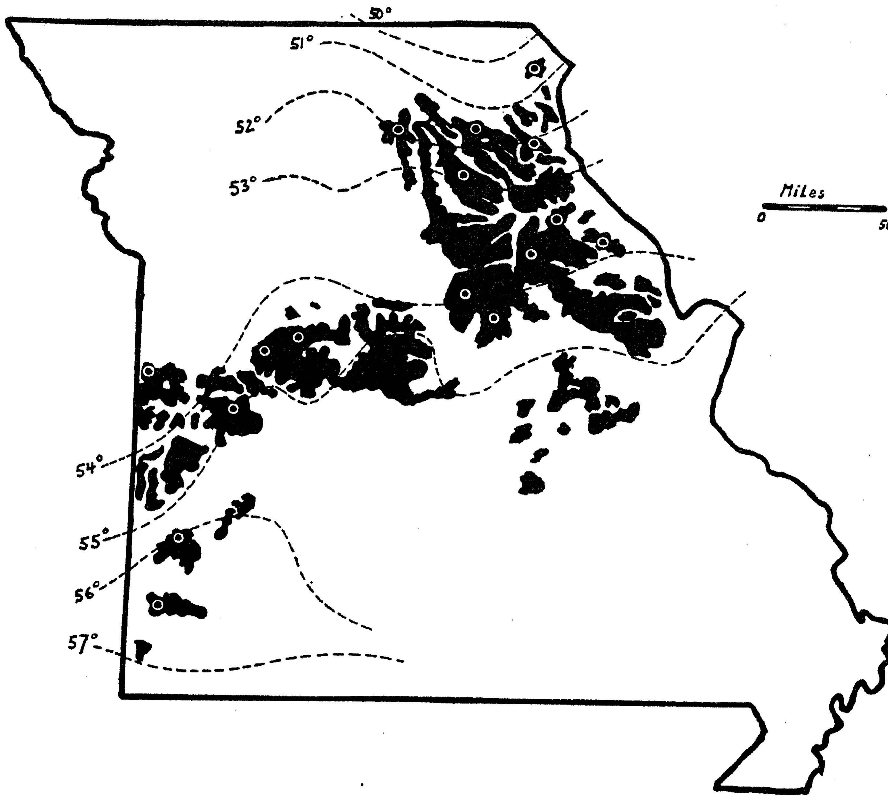

Fig. 12. Location of flat prairie soils in Missouri and annual isotherms in degrees Fahrenheit (50°F. = 10.00°C. and 57°F. = 13.89°C.)

TABLE 13.—CLIMATOLOGICAL DATA OF STATIONS SURROUNDING THE MISSOURI FLAT PRAIRIE SOILS

Climatological data of stations surrounding the Missouri flat prairie soils

Station	Altitude		Mean Annual Temperature		Humidity factor
	feet	*meters*	°*F.*	°*C.*	
Keokuk, Iowa	614	187	52.3	11.28	336
St. Joseph, Mo.	967	294	54.0	12.22	261
Columbia, Mo.	784	239	54.5	12.50	354
Kansas City, Mo.	963	293	54.8	12.67	276
Springfield, Mo.	1,224	344	55.6	13.11	352
St. Louis, Mo.	567	173	56.0	13.33	291

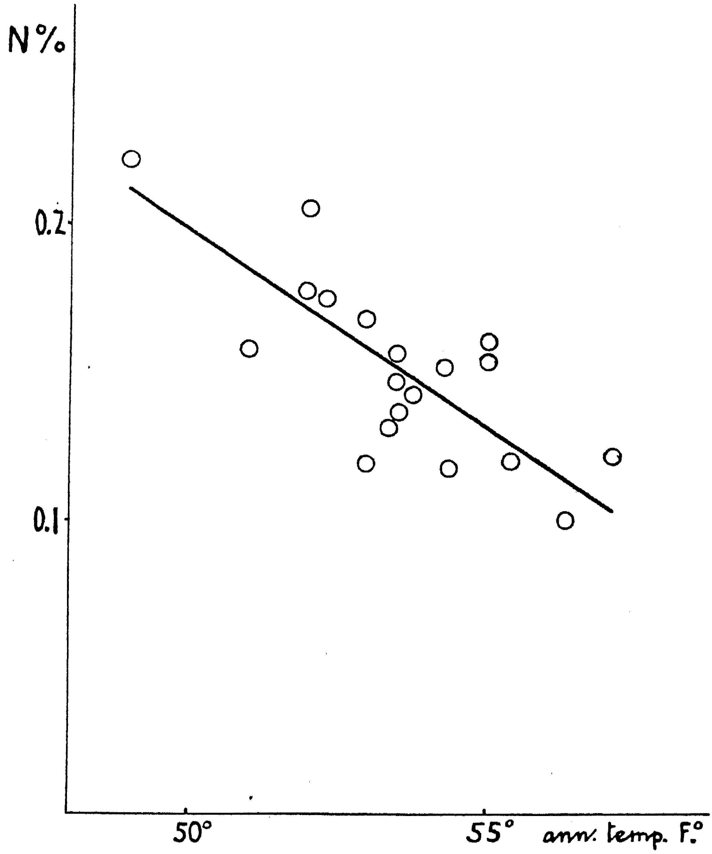

Fig. 13.—Nitrogen-temperature relation of the flat prairie soils of Missouri.

TABLE 14.—NITROGEN-TEMPERATURE RELATION IN THE LEVEL PRAIRIE SOILS OF MISSOURI
Humidity factors 261-354

Mean Annual Temperature		County	Number of Nitrogen Values	Average Total Nitrogen Content	Soil Type
°F.	*°C.*			*per cent*	
49	9.44	Wapello, Ia.	1	0.222	Putnam silt loam
51	10.56	Clark, Mo.	1	0.158	Putnam-like Grundy
52	11.11	Knox, Mo.	4	0.178	Putnam silt loam
52	11.11	Harrison, Mo.	3	0.206	Putnam silt loam
52.3	11.28	Lee, Iowa	1	0.177	Putnam silt loam
53	11.67	Ralls, Mo.	3	0.119	Putnam silt loam
53	11.67	Shelby, Mo.	8	0.169	Putnam silt loam
53.4	11.89	Cass, Mo.	1	0.133	Oswego silt loam
53.5	11.94	Marion, Mo.	10	0.145	Putnam silt loam
53.5	11.94	Macon, Mo.	9	0.157	Putnam silt loam
53.5	11.94	Pike, Mo.	1	0.135	Putnam silt loam
53.7	12.06	Audrain, Mo.	4	0.142	Putnam silt loam
54.4	12.44	Pettis, Mo.	6	0.152	Oswego silt loam
54.5	12.50	Boone, Mo.	1	0.118	Putnam silt loam
54.9	12.72	Callaway, Mo.	3	0.155	Putnam silt loam
55	12.78	Johnson, Mo.	2	0.161	Oswego silt loam
55.6	13.06	Henry, Mo.	8	0.121	Cherokee silt loam
56.4	13.56	Barton, Mo.	1	0.100	Cherokee silt loam
57.2	14.00	Newton, Mo.	1	0.122	Cherokee silt loam

Organic Matter-Temperature Relation in the Eastern United States

The discussion thus far has been confined to correlations between temperature and soil nitrogen only. The nature of the decomposition process of organic matter, as discussed on page 15, suggests that formula (XI) also holds for total organic carbon (see Wollny's curve of CO_2 evolution), and consequently for organic matter, since multiplying the percentage of total organic carbon by the conventional humus factor 1.742 gives the percentage of total organic matter in the soil.

The region selected for the study of the organic matter-temperature relationship belongs to the eastern United States, including the New England states, New York, New Jersey, Delaware, Maryland, Virginia, North Carolina, South Carolina, Georgia, Alabama, and Florida. The parent material from which the soils are derived consists partly of igneous and metamorphic rocks (Piedmont Plateau), partly of sedimentary deposits (Coastal Plain). The native vegetation has been classified by Shantz as "southern hardwood forest" (oak-pine phase) and "southeastern pine forest" (longleaf-loblolly-slash pine).

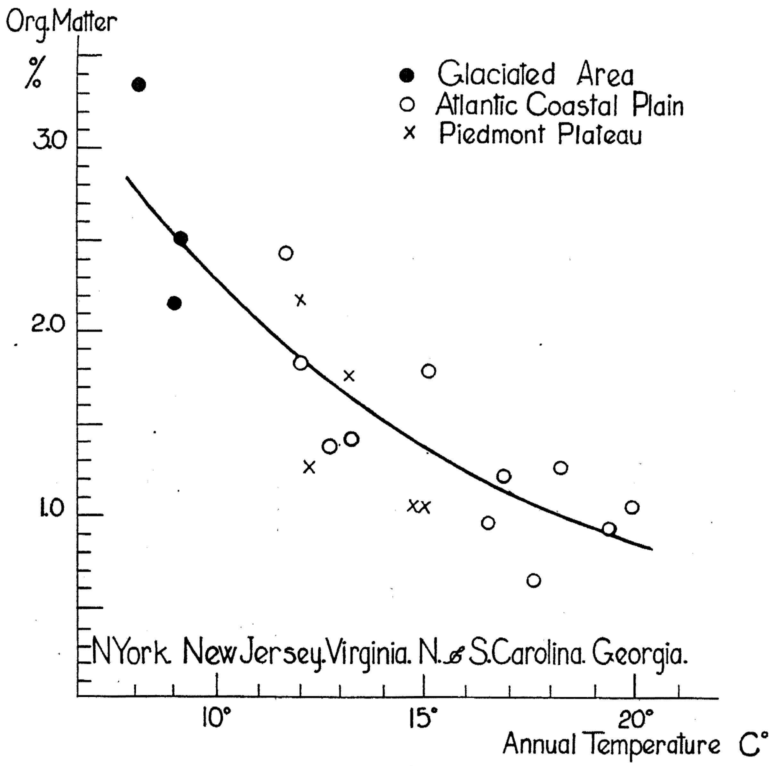

Fig. 14. Organic matter-temperature relationship in the eastern United States.

Organic matter analyses of eighteen counties, lying mainly within the Piedmont Plateau and Atlantic Coastal Plain were taken from the "Field Operations of the Bureau of Soils 1902 and 1903".[74] Only predominating, well drained upland soils of loam and sandy loam textures were considered. Each point in Figure 14 represents the average organic matter content of the surface soils of an entire county.

In order to follow the trend of the organic matter temperature relation north of the Piedmont Plateau and Costal Plain, three counties from the New England states and New York (glaciated areas) were included in this investigation. The humidity factors of these counties are somewhat higher, (namely N. S. Q. 400-500), than those of the southern counties which lie between N. S. Q. 300 and 400. In fitting the curve, less weight was given to the three northern points in the graph, which would make the slope of the curve even steeper than that shown in Figure 14.

The computation of the calculated values in Table 15 is based on the formula:

$$O.M = 6.50\, e^{-0.104 T}\Big|_{8^\circ}^{20^\circ} \qquad \text{(XIX)}$$

where O. M. means average organic matter content of the surface soils of a county in percentage, T the mean annual temperature in Centigrade.

TABLE 15.—SUMMARY OF ORGANIC MATTER VALUES

Annual Temperature		State	County or Area	No. of Soil Types per County	No. of Analyses per County	Average Organic Matter Content of Loamy Soils per County				
						Glaciated Region	Piedmont Region	Coastal Plain	Calculated Value	Deviation
F°.	*C°.*					*per cent*	*per cent*	*per cent*	*per cent*	
46.7	8.17	New York	Syracuse	3	8	3.35	----	----	2.78	0.57
48.2	9.00	Connecticut	Valley	4	7	2.16	----	----	2.55	0.39
48.4	9.11	New York	Big Flats	2	6	2.51	----	----	2.52	0.01
52.1	11.7	New York	Long Island	3	7	----	----	2.43	2.03	0.40
53.6	12.00	New Jersey	Trenton	5	14	----	2.18	1.82	1.87	0.31 0.05
53.8	12.17	Virginia	Leesburg	6	13	----	1.27	----	1.83	0.56
55.0	12.78	Delaware	Dover	2	5	----	----	1.37	1.72	0.35
55.8	13.22	Virginia	Albemarle	2	5	----	1.74	----	1.64	0.10
56.0	13.30	Maryland	Worcester	2	6	----	----	1.42	1.63	0.21
58.7	14.83	N. Carolina	Hickory	2	6	----	1.09	----	1.39	0.30
59.1	15.06	S. Carolina	Campobello	1	2	----	1.09	----	1.36	0.27
59.4	15.22	Virginia	Norfolk	3	9	----	----	1.70	1.33	0.46
61.9	16.61	N. Carolina	Graven	2	6	----	----	0.98	1.16	0.18
62.5	16.94	S. Carolina	Darlington	5	9	----	----	1.22	1.12	0.10
63.9	17.72	Alabama	Perry	2	6	----	----	0.63	1.03	0.40
64.9	18.28	Georgia	Fort Valley	2	4	----	----	1.27	0.97	0.30
67.0	19.44	Alabama	Mobile	3	7	----	----	0.95	0.86	0.09
68.0	20.00	Florida	Gadsden	3	8	----	----	1.06	0.81	0.25

In a recent paper on "Some Carbon-Nitrogen Relations in Scils" (Soil Science 30: 257-266, 1930) W. R. Leighty and E. C. Shorey published a series of nitrogen and carbon analyses of cultivated soils from the eastern United States. The data for timbered upland soils of loam and sandy loam texture speak in favor of a pronounced nitrogen and organic matter temperature relationship as seen from the following table:

NITROGEN-ORGANIC MATTER-TEMPERATURE RELATIONSHIP IN EASTERN UNITED STATES AFTER DATA FROM LEIGHTY AND SHOREY

State	Number of Analyses	Approximate Annual Temperature	N.	Organic Matter (C×1.724)
		C.°	*per cent*	*per cent*
Maine	1	4°	0.227	5.17
Pennsylvania	4	11°	0.176	3.12
New York	4	11.2°	0.116	2.78
New Jersey	4	11.5°	0.125	2.31
Virginia	7	15°	0.074	1.36
North Carolina	6	16°	0.047	1.42
South Carolina	4	17°	0.028	0.92
Georgia	4	18.5°	0.044	1.15
Florida	1	20°	0.041	1.74

The Trend of the Carbon-Nitrogen Ratio as Affected by Temperature

The work of Sievers and Holtz, Waksman and others[66 78 79], has brought out the importance of the C:N ratio in soil fertility investigations. In soils of temperate regions the carbon-nitrogen ratio tends toward a constant value, having the magnitude of 10 to 12, while in the original plant materials the ratio varies between 16 and 200. According to the general character of the theoretical equation (XI) which demands that under low temperatures the composition of the organic matter of the soil approaches that of the undecayed material (constant a), one would expect that the carbon-nitrogen ratio is not an absolute constant, but varies itself with temperature, in that it becomes wider as one goes from south to north.

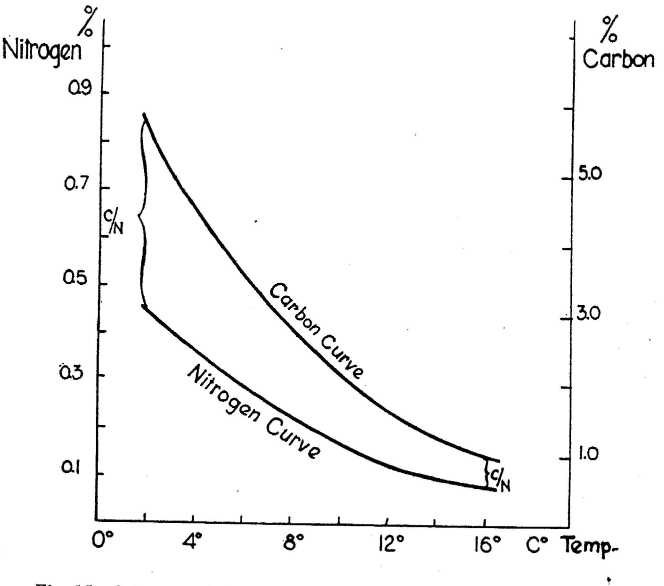

Fig. 15. Schematical sketch, illustrating the conditional widening of the C/N ratio with decreasing temperature as demanded by equation (XI).

Figure 15 illustrates schematically the trend of the nitrogen curve (lower line) and the carbon curve (upper curve) and the conditional widening of the C/N ratio, as demanded by equation (XI). In Table 16, carbon-nitrogen ratios of semi-arid and semi-humid grassland soils[58,17,27,61,70] have been arranged into temperature classes, and the class averages were plotted against temperature in the diagram of Figure 16. The effect of temperature upon the magnitude of the C/N ratio can be stated in the following way: *with decreasing temperature the C:N ratio seems to become wider.** S. Waksman[80] explains this variation of the C:N ratio as follows: "This is due both to differences in the nature of the organisms active in the decomposition of the plant residues and of those microorganisms which bring about the decomposition of the soil organic matter."

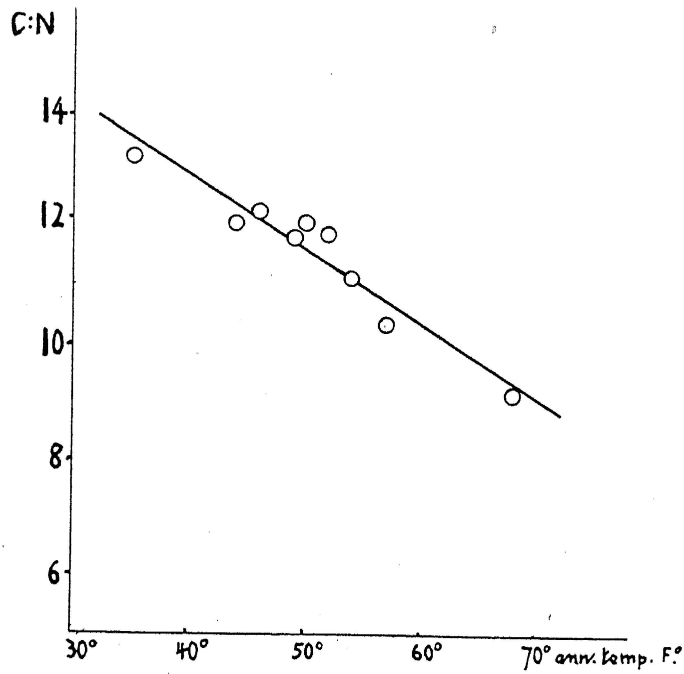

Fig. 16. Variation of carbon-nitrogen ratios with temperature in the Great Plains and Prairie Region.

In this connection a comparison of the nitrogen curve of the midwestern timber soils (Figure 11) and the organic matter curve of the eastern timber soils (Figure 14) reveals an interesting feature of the organic matter temperature relationship. Since the timber soils of Wisconsin, Illinois, western

*It will be noted from Table 16 that the mean errors of the C:N averages are quite large. Further confirmation of the temperature effect on the C:N ratio would be desirable.

TABLE 16.—CARBON-NITROGEN RATIO AND TEMPERATURE (LOAMS AND SILT LOAMS)

Temperature		State	C/N	Number of Values (Counties)
°F.	°C.			
35.0	1.67	Saskatchewan (Canada)	13.25±0.555	6
44.0	6.67	Iowa	12.21±0.210	10
46.0	7.78	Iowa	12.30±0.122	4
48.0	8.89	Iowa	11.85±0.191	19
50.0	10.00	Iowa, Nebraska	12.11±0.136	14
52.0	11.11	Nebraska	11.90±0.383	4
54.0	12.22	Nebraska, Kansas	11.15±0.470	6
57.0	13.89	Kansas	10.30±0.681	3
68.0	20.00	Texas	9.1	76

Kentucky, western Tennessee, and Mississippi are subject to similar annual climatic conditions as those of the Atlantic Coast States, the possibility exists that the organic constituents of the soils of the two regions also have similar properties. Several calculated nitrogen averages of midwestern timber soils are shown in Column 3 of Table 17 the climatically corresponding organic matter figures from the eastern soils are listed in Column 4. Division of the latter values by the conventional humus factor 1.742 gives the percentage of total organic carbon (Column 5). If one divides now the carbon figures of the eastern soils by the climatically corresponding nitrogen figures of the midwestern soils, one obtains a surprisingly constant value averaging 10.8 for the C:N ratio. (Column 6). In other words, the eastern organic matter-temperature curve and the midwestern nitrogen temperature curve apparently are identical curves in that they differ only by a constant, the C:N ratio times 1.742.

TABLE 17.—COMPARISON OF THE ORGANIC MATTER TEMPERATURE CURVE OF THE EASTERN UNITED STATES WITH THE NITROGEN TEMPERATURE CURVE OF THE MIDDLE WEST

Temperature		Calculated nitrogen content of midwestern soils	Calculated organic matter content of eastern soils	Calculated carbon content of eastern soils. O.M.:1.742	Carbon-Nitrogen ratio
C.°	F.°	%N	%O.M.		C/N
8	46.4	0.148	2.83	1.623	11.0
10	50.0	0.121	2.30	1.321	10.9
12	53.6	0.098	1.87	1.073	10.9
14	57.2	0.080	1.52	0.872	10.9
16	60.8	0.066	1.23	0.706	10.7
18	64.4	0.054	1.00	0.574	10.6
20	68.0	0.044	0.81	0.465	10.6
					10.8 avg.

Mathematical Discussion

Judging from the various graphs and tables it is evident that all nitrogen and organic matter temperature relations can be satisfactorily described by the equation

$$N = \frac{a}{1+e^{kT}} \qquad \text{(XI)}$$

Deduction and observation agree closely. Nevertheless one must keep in mind that all the experimental curves represent only the lower branch of the theoretical sigmoid curve, and it is quite possible that in colder and in arctic regions the formula may fail. As a matter of fact, it must fail in the extreme North because the organic matter produced by vegetation can no longer be considered a constant. It differs too much from the amount and quality of organic material formed in temperate and subtropical regions. Moreover, the nature of the microbiological population of the soil may also change with the latitude. At a certain, (yet unknown), temperature the nitrogen temperature relationship contains a maximum and then decreases again because of too scanty a vegetation.—Due to the fact that very high temperatures retard the decomposition velocity of organic matter (negative rate of change, see page 13), the possibility exists that in tropical regions the nitrogen and organic matter content (including the C:N ratio) increase again, in other words the nitrogen temperature relation may also have a minimum.

The constant "a" in equation XI which is obtained by graphical methods stands for the nitrogen content of the vegetation and varies between 1.00 and 1.80 per cent (average 1.54 per cent N). Actual analyses of prairie and timber vegetation furnish values laying between 1 and 2 per cent N. This agreement in the order of magnitude between chemical analyses of the organic matter produced by vegetation and its value computed from soil nitrogen analyses is remarkable and speaks favorably for the soundness of the general nature of equation XI.

The constant "k" may be interpreted as "velocity constant" of the decomposition process. It is given by the expression:

$$k = \frac{1}{T}\log_e\frac{a-N}{CN} \qquad \text{(XX)}$$

Inspection of the k values of the various equations indicates that within similar humidity districts k is independent of the type of vegetation and has about the same magnitude both for nitrogen and organic matter curves (equations XIII-XVII). In arid regions k seems to be somewhat smaller than in humid regions.

For the purpose of obtaining a simple differential coefficient, the nitrogen temperature relations can all be described by the empirical function

$$(N)_H = Ce^{-k_1{}_0^2 T_\circ^{2'}} \qquad \text{(XXI)}$$

in which C and k are constants. For curves 1, 2, and 5 the values of k_1 are 0.073, 0.095, 0.101 respectively. After taking logarithms the equation XXI becomes

$$\log_e (N)_H = \log_e C - k_1 T \qquad \text{(XXII)}$$

and its first differential coefficient has the form:

$$\left(\frac{\partial N}{\partial T}\right)_H = -k_1 N \qquad \text{(XXIII)}$$

This differential coefficient will be used later for computing the general nitrogen-climate equation.

A few remarks as to the statistical treatment of the numerous available data may be added[42]. The dots in the nitrogen-temperature diagrams represent averages of their respective temperature classes (except curve 8). The question naturally arises as to how widely the single values are scattered about the average. Are these class-means reliable enough to be put in a functional relation to temperature? Information is obtained from the mean error (or probable error, which is 0.6745 times the mean error) for the class averages, and from the correlation ratio for the deviation of the values about the curve. The mean error was calculated according to the common formula

$$m = \sqrt{\frac{\Sigma v^2}{n(n-1)}} \qquad \text{(XXIV)}$$

where m represents mean error, n total number of values, and Σ the sum of the squares of the numbers formed by subtracting each value from the arithmetical mean of the whole class.

As an index of the deviation of the single values (county units) about the curve, the correlation ratio was chosen. It measures the degree of relationship between the single nitrogen values and their corresponding temperature in-so-far as this relationship may be described by a curve passing through the mean of every temperature class. If the relationship is ideal, if there is no scatter about the curve filled in this way, η will have a value of 1. If there is no relationship, if the scatter about the curve is as great as the dispersion about the mean of all nitrogen values, will have a value of zero. The formula used is

$$\eta = \sqrt{1 - \frac{\sigma NT^2}{\sigma N^2}} \qquad \text{(XXV)}$$

where η represents correlation ratio, σNT^2 the standard deviation of all single nitrogen values about a line passing through the mean of the various temperature classes, and σN^2 the standard deviation of all single nitrogen values about their arithmetical average. This correlation ratio of the various curves is listed in Table 18. According to the scale of Chaddock, the η values in Table 18 indicate a high degree of association between temperature and soil nitrogen or soil organic matter.*

*The correlation ratio was applied merely to demonstrate a significant negative association between soil nitrogen and temperature, and no attempt was made to obtain mathematical formulas which might give a better fit than those developed theoretically.

The deviation of nitrogen values may be due to differences in sampling (variations in depth) or to factors which hasten or delay the decomposition process in the field above or below "normal". Such factors are: physical and

TABLE 18.—CORRELATION-RATIOS OF THE VARIOUS SOIL REGIONS

Curve	η
Semi-arid region, grassland	0.91
Semi-humid upland soils (predominating prairie)	0.90
Semi-humid terrace soils (predominating timber)	0.78
Semi-humid bottom soils (timber)	0.78
Humid upland soils (prairie)	0.89
Humid upland soils (timber)	0.84
Flat prairie soils of Missouri	0.77
Humid eastern United States (organic matter)	0.87

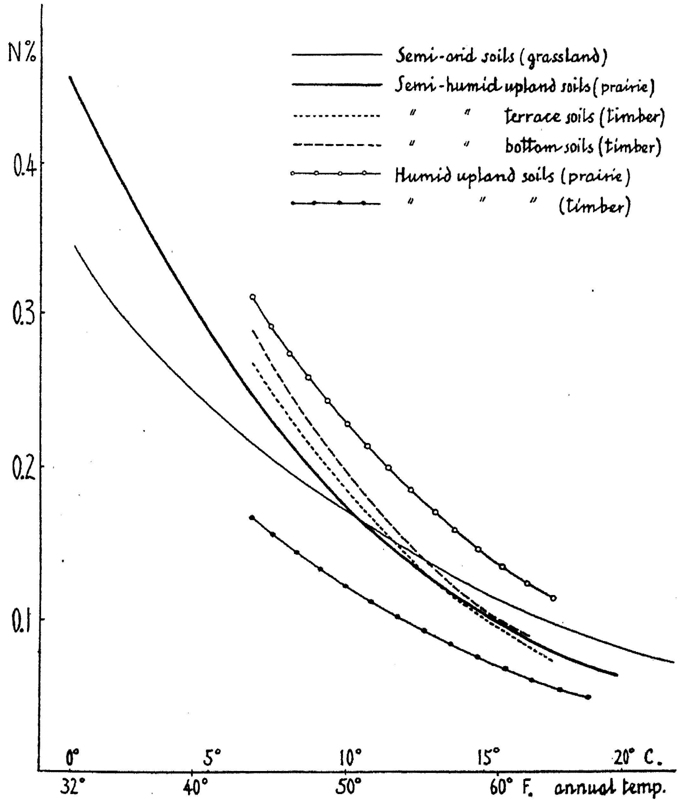

Fig. 17. Graphic summary of nitrogen-temperature relations.

chemical properties of the soil, age, topography, geological origin, soil climate, vegetation and cultivation.

Summary of the Nitrogen and Organic Matter-Temperature Relation

Investigation of the nitrogen and organic matter-temperature relationship within the United States has revealed the following interesting facts:

1. Within regions of similar moisture conditions, the nitrogen and organic matter content of upland, terrace and bottom land soil, including both prairie and timber vegetation, decreases from north to south.

2. Mathematically speaking, the decrease can be represented by a negative exponential function, its differential coefficient being $\left(\frac{\partial N}{\partial T}\right)_H = -k_1N$.

3. The following general rule applies to all curves studied: *For each fall of* 10°*C. in annual temperature, the average total nitrogen and organic matter content of the soil increases* 2-3 *times, provided the precipitation-evaporation ratio is kept constant.*

4. The C:N ratio seems to become somewhat wider with decreasing temperature.

5. Within large areas of equal moisture conditions, but relatively wide temperature variation, and for soils having similar textural conditions, the importance of soil forming factors in determining soil nitrogen can be represented by the following descending series:

Temperature > Vegetation > Topography > Parent Material

where > means "greater than" or "more important than".

6. A graphical summary of nitrogen temperature relations is given in Figure 17.

THE NITROGEN-ORGANIC MATTER-HUMIDITY FACTOR RELATION

The nitrogen humidity factor relation is conveniently written in the following form:

$$(N)_T = f \text{ (humidity factor)} \qquad \text{(XXVI)}$$

where the subscript T denotes that the temperature is kept constant; that is to say, the correlation between nitrogen and humidity factors is investigated only for such soils as have similar temperatures or in other words which lie along an isotherm[23]. After the mathematical form of this equation is known, its differentiation will furnish the required partial derivative $(\partial N/\partial H)_T$.

Historical

The influence of moisture on the formation of humus in the soil was discussed by R. Lang[33] in 1918. He said: "The more humid a region, the greater the amount of organic matter produced by vegetation, but the smaller the decomposition by micro-organisms, hence the humus content of the soil increases with increasing moisture." No data or graphs to illustrate this important conception were given.

An attempt to correlate quantitatively the soil organic matter with humidity, was undertaken by L. Smolik[68]. He analyzed the humus of numerous samples of degraded Tschernosems and podsolized soils from Czechoslovakia, and correlated the results with Lang's rain factor (precipitation divided by temperature). According to Smolik's data, which are summarized in Table 19, the amount of total humus (total organic matter) shows no variation with the rain factor, while the chemical composition of the humus indicates a climatic relationship.

TABLE 19.—CHEMICAL COMPOSITION OF HUMUS AND CLIMATE (AFTER SMOLIK)

Location	Rain factor (annual)	Amount of humus		Chemical composition of total humus				
		Total	Colloidal	C	N	H	C:H	C:N
Hulin	53.1	3.78	2.11	35.4	1.6	8.5	4.2	22.2
Slapanice	70.9	3.23	1.35	28.6	1.2	9.8	2.9	23.1
Radomin	91.1	3.55	0.76	19.6	0.7	10.9	1.8	29.9
Freustat	144.1	3.45	1.14	17.1	0.8	10.9	1.6	21.0

In a study of alpine vegetation and soil formation, the author[19] drew a humus-moisture curve based on N. S. Quotients (Precipitation divided by absolute saturation deficit of air). This was found to be of exponential nature, but the number of points was not great enough to make the curve very significant.

F. J. Sievers and H. F. Holtz[66], also working in mountain regions found that soil nitrogen and organic matter increase with higher altitude and its correspondingly higher precipitation. Some of their interesting figures are given in Table 20.

TABLE 20.—VARIATION OF SOIL ORGANIC MATTER WITH ALTITUDE IN FINE TEXTURED SOILS OF THE ARID REGIONS OF THE STATE OF WASHINGTON, U. S. A. (AFTER SIEVERS AND HOLTZ)

Altitude feet	Annual Precipitation inches	% of total N in soil	Carbon:nitrogen ratio
1050	7.5	0.054	12.7
1050	8.5	0.052	10.7
1400	10.0	0.083	12.1
1400	12.0	0.091	12.4
1565	12.5	0.060	11.0
1560	15.5	0.106	10.6
1525	16.0	0.082	13.4
1600	16.5	0.092	13.3
1800	17.0	0.108	13.4
2550	21.5	0.202	12.9

One of the best curves published along this line of investigation is that of J. C. Russell and McRuer[61] who correlated the nitrogen content of virgin Nebraska soils with annual rainfall. The relationship is perfectly linear, but after the authors reduce the soils to a common hygroscopic coefficient, in order to eliminate the texture variations, the relationship becomes non-linear. Fortunately Russell's curve is practically free from a common mistake in studies of soil moisture relationships, namely the failure of comparing regions of various temperatures. Whether or not the results in Tables 19 and 20 are appreciably influenced by differences in temperature cannot be said, but even the use of the rainfactor or the N. S. Quotient does not take account of the temperature effect itself.

Experimental Part

The 628 nitrogen values used were drawn from three sources, (1) soil samples which were collected by the author and analysed at the Missouri Experiment Station (samples from Missouri and Kansas), (2) soil samples secured from other states through their respective soil surveyors, but analysed at the Missouri Experiment Station (samples from Colorado, Kansas, New Jersey), and (3) soil analyses taken from soil bulletins [1,16,72] or received through private communication (Illinois, Texas, Ohio, Indiana). As in the nitrogen temperature relation the nitrogen values of each county, ranging from 2-18 were averaged separately. This average was taken as the comparable unit and plotted in the graphs (white points and light crosses), against the moisture values. The humidity factor (N. S. Q.) for each county was obtained in the following manner. In a system of coordinates with meridians as abscisse and N. S. Q. as ordinates, the N. S. Q. of meteorological stations lying around the isotherms mentioned, were plotted and connected by a smooth line. The humidity factor (N. S. Q.) of each county was then determined graphically from this line on the base of its average meridian. To simplify the mathematical treatment, N. S. Q. class intervals were formed and their nitrogen averages only were tabulated (black points and heavy crosses in the graphs). In order to exclude variations in soil texture and topography, the investigation was restricted to loams and silt loams of gently rolling upland soil types.*

Temperate Region.—The counties selected in the temperate region form a narrow belt extending from the Rocky Mountains (Colorado) eastward to the Atlantic Coast passing through northern Kansas and Missouri, central Illinois, Indiana and Ohio to north central New Jersey. (Figure 18). The annual temperature of the band varies only between 10.6-11.7°C. In other words the soils investigated are closely centered around the annual isotherm of 11°C.

*The flat prairies, e. g. Putnam silt loam, were excluded.

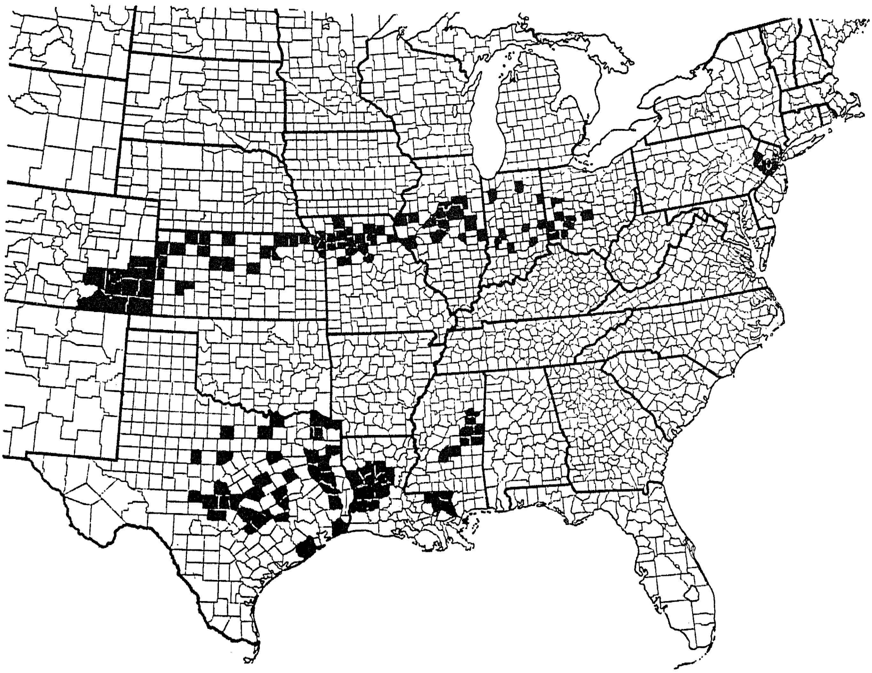

Fig. 18. Map Showing the Location of the Counties from which Soil Nitrogen Analyses Were Obtained for the Study of the Nitrogen Humidity Factor Relation.

The assembled nitrogen values of each county are shown in Figure 19, and a summary of the nitrogen averages of the N. S. Q. classes is given in Table 22.

At first sight, discontinuity appears as a striking feature of the nitrogen humidity factor relationship. By discontinuity is meant the particular behavior of the function exhibiting an abrupt break or stop in the curve. On examining Figure 19 one observes a gradually ascending, uniform curve which suddenly ends at the humidity factor value of about 400. The continuation then appears at an entirely different position of the diagram. As a matter of fact, the nitrogen moisture relationship of the prairie-timber transition region[11] has to be split off into two separate curves according to the original vegetational cover which seems to exert a dominating influence on the nitrogen level of the soils in question.

There are numerous equations existing which would satisfactorily describe the regularly ascending logarithmical curve, as given for the *grassland soils*. Preference goes to an equation which gives a simple and significant first differential coefficient. The similarity of the curves to the well known formula of Mitcherlich is obvious. Mitcherlich's logarithmic curve with

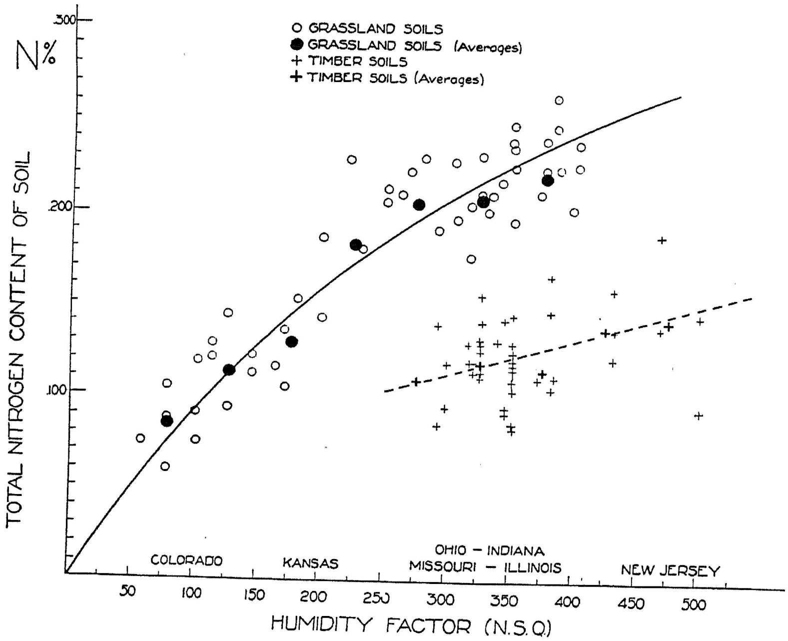

Fig. 19. Soil nitrogen-humidity factor relation along the annual isotherm of 11°C. White points and light crosses represent county averages; black points and heavy crosses, nitrogen averages of N. S. Q. class intervals.

decreasing increments, quite commonly applied to growth processes, has the form:

$$(N)_T = A\ (1 - e^{-k_2H}) \qquad \text{(XXVII)}$$

where N means total average nitrogen content of the soil in percentage, H the humidity factor (N. S. Q.) and A, k_2, e, are constants. Taking logarithms the equation can be written

$$\log_e (N)_T = \log_e A + \log_e (1 - e^{-k_2H}) \qquad \text{(XXVIII)}$$

Its differential coefficient then assumes the form:

$$\left(\frac{\partial N}{\partial H}\right)_T = \frac{k_2 e^{-k_2H} N}{1 - e^{-k_2H}} \qquad \text{(XXIX)}$$

For the grassland curve in the temperate region equation XXVII takes the form:

$$N_{11^\circ C} = 0.320\ (1 - e^{-0.0034H})_0^{400} \qquad \text{(XXX)}$$

The close agreement between observed and calculated values for the class averages can be seen in Table 21.

In the case of the timber curve, the trend of the relationship is not so obvious. There exists no doubt that the nitrogen content of the originally timbered soils is decidedly lower than that of the prairie soils of the same climatic district, but the scatter of the data is too great to suggest any definite mathematical relationship. The slightly ascending straight line in Figure 19 is to be considered a mere suggestion.

Although the total nitrogen content of the soil varies with humidity factors, it is quite essential to note that the carbon-nitrogen ratio remains fairly constant along the 11°C. isotherm as seen from Table 22.

TABLE 21.—VALUES OF THE C:N RATIO ALONG THE 11°C. ISOTHERM

N. S. Q.	State	Carbon-Nitrogen Ratio	Vegetation
200-300	Kansas	11.15±0.470	Grassland
	Nebrasks	11.90±0.383	
300-400	Illinois	11.79±0.229	Grassland
		11.03±0.272	Timber
400-600	New Jersey	10.82±0.250	Timber

The average C:N ratio has a value of about 11.3 and is nearly the same both in timber (10.9) and grassland soils (11.6). It will be remembered that the ratio probably varies with temperature (page 41), being wider in the North than in the South. These two statements do not necessarily contradict each other, because we are dealing with two independent variables, moisture and temperature.

From the constancy of the C:N ratio we may conclude that formula XXVII is also valid for total organic carbon, in other words, also the organic matter content of grassland soils increases logarithmically with humidity factors, while in forest soils the humus content of the soil changes little with moisture values, as judged from analyses of cultivated fields.

Subtropical Region.—The belt of constant temperature chosen in the subtropical region is somewhat wider than that of the temperate region. It varies between the temperatures 17.8-20.0°C (annual isotherm of 19°C.) and includes territory of central Texas, Louisiana and Mississippi (see Figure 18). Table 23 gives information as to the data collected and Figure 20 shows the graphical representation of the nitrogen moisture relationship in the South.

Again the function has to be divided into two separate curves, one for grassland soils and one for timber soils. Particular attention should be directed to the relative position of the two curves as compared with the findings in the temperate regions. Both grassland and timber soils nitrogen values in the subtropical region are much lower than those of region farther north which is in perfect agreement with the nitrogen temperature relation, discussed in the foregoing chapter.

TABLE 22.—NITROGEN-HUMIDITY FACTOR RELATION IN THE TEMPERATE REGION (ANNUAL TEMPERATURE 11°C.)

State	Annual humidity (N.S.Q.) factor		Mean annual rainfall	Number of counties		Number of N values		Average total N content of grassland soils			Average total N content of timber soils (observed)
	Class interval	Mid-point		Grass-land	Timber	Grass-land	Timber	Ob-served	Calcu-lated	Difference	
			inches	*units*	*units*						
Colorado	50-100	75	12	4	—	13	—	0.082	0.072	+0.010	—
Colorado, Kansas	100-150	125	12-15	9	—	27	—	0.112	0.111	+0.001	—
Kansas	150-200	175	15-20	4	—	10	—	0.127	0.143	−0.016	—
Kansas	200-250	225	20-25	4	—	10	—	0.184	0.171	+0.013	—
Kansas, Missouri	250-300	275	25-30	6	2	39	7	0.205	0.194	+0.011	0.110
Missouri, Illinois, Ohio	300-350	325	30-42	9	15	65	33	0.207	0.214	−0.007	0.118
Missouri, Illinois, Indiana, Ohio	300-400	375	30-45	13	23	21	73	0.222	0.230	−0.008	0.117
New Jersey	400-450	425	45-47	—	3	—	11	—	—	—	0.138
New Jersey	450-500	475	47-51	—	4	—	5	—	—	—	0.140

TABLE 23.—NITROGEN-HUMIDITY FACTOR RELATION IN THE SUBTROPICAL REGION. (ANNUAL TEMPERATURE 19°C.)

State	Annual humidity (N.S.Q.) factor		Mean annual rainfall	Number of counties		Number of N values		Average total N content of grassland soils			Average total N content of timber soils		
	Class interval	Mid-point		Grass-land	Timber	Grass-land	Timber	Ob-served	Calcu-lated	Differ-ence	Ob-served	Calcu-lated	Differ-ence
			inches	*units*	*units*								
Texas	100-200	150	22-40	6	13	44	69	0.083	0.073	+0.010	0.058	0.050	+0.008
Texas, Louisiana	200-300	250	35-55	6	20	13	139	0.095	0.092	+0.003	0.046	0.050	−0.004
Louisiana, Mississippi	300-400	350	50-64	5	8	19	30	0.096	0.101	−0.005	0.052	0.050	+0.002

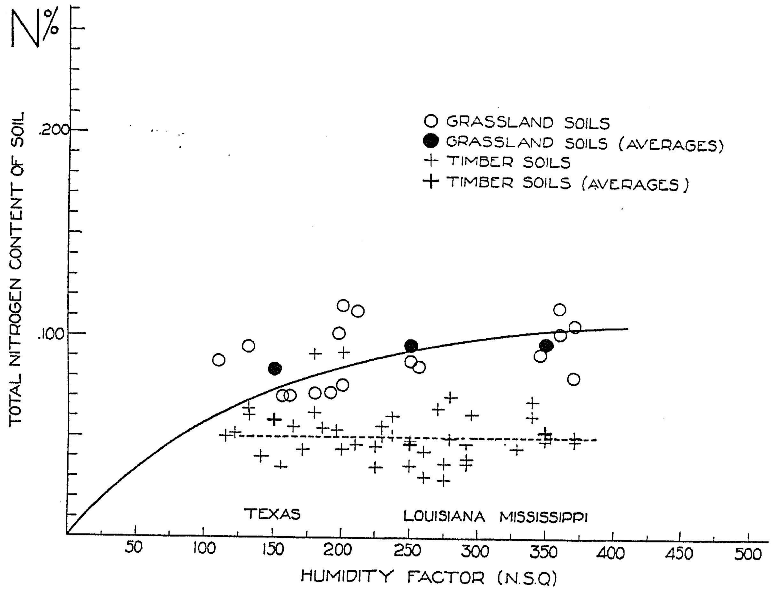

Fig. 20. Soil nitrogen-humidity factor relation along the 19°C. annual isotherm. White points and light crosses represent county averages; black points and heavy crosses, nitrogen averages of N. S. Q. class intervals.

Applying Mitcherlich's formula to the trend of the grassland curve furnishes the following specific equation:

$$N_{19^{\circ}C} = 0.110\ (1 - e^{-0.0073H})_0^{400} \qquad \text{(XXI)}$$

In the case of the subtropical timber soils it was quite contrary to expectations to find that the nitrogen values are grouped around a straight line parallel to the abscissa. This leads to the suggestion that the nitrogen content of the southern timber soils investigated is independent of the climatic moisture conditions, at least between N. S. Q. 100-400. Apparently, high temperature keeps the nitrogen content of these subtropical soils on such a low level that climatic moisture conditions become of subordinate importance in soil nitrogen maintenance. The line connecting the nitrogen average for the timber soils (cultivated) has the simple mathematical expression:

$$N_{19^{\circ}C} = \text{constant, namely } 0.05\% \qquad \text{(XXXII)}$$

It will be observed that the variation or dispersion of the subtropical timber values has a considerably smaller magnitude than that of the temperate timber soils, a characteristic which is quite general for the nitrogen climate relationship. Examination of the various tables referring to the nitrogen-temperature relationship reveals clearly that the absolute mean error, which might be considered an index of the magnitude of the scattering becomes wider

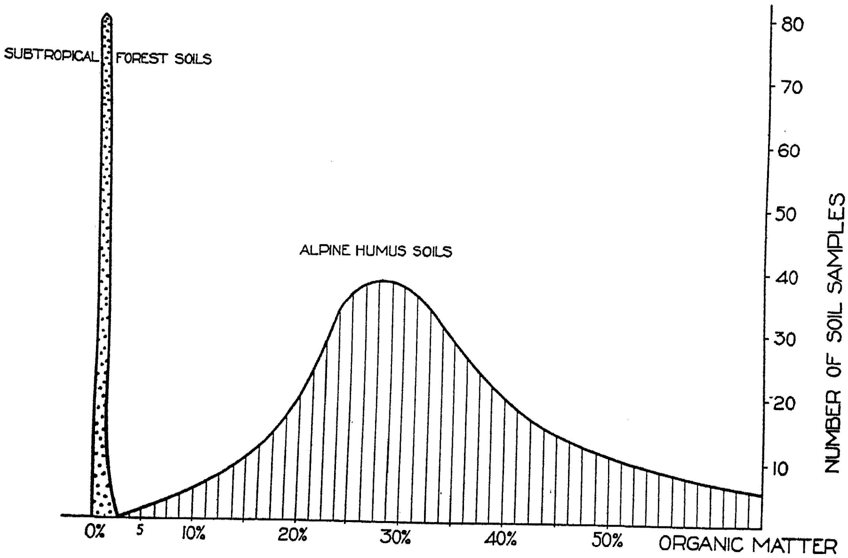

Fig. 21. Frequency diagrams of the organic matter content of 100 subtropical timber soils and 100 alpine humus soils.

as one goes north. Figure 21 illustrates contrastingly this behavior for soils of two extreme regions, namely for the humus content of subtropical timber soils (cultivated) and virgin alpine humus soils[19,24,81]. Both curves are drawn on the bases of 100 analyses. The average humus content of 100 subtropical timber soils is about 1% and all analyses lie closely around this figure. The distribution curve for alpine humus soils also exhibits a pronounced mean (at about 30% organic matter), but there are numerous analyses which differ widely from the average, thus producing a relatively flat curve. The conclusion follows, that a random sample of subtropical timber soil is more representative than one of the alpine humus soils, in regard to the general soil organic matter conditions of the particular region.

Discussion.—Ignoring the vegetational factor and consequently the discontinuity of the nitrogen-moisture relationship would lead to serious difficulty in explaining the lower nitrogen content of humid soils (New Jersey) as compared with the high nitrogen content of the slightly arid and sub-humid soils of Kansas and Missouri. Thus, Lang's general statement[33] that soil organic matter increases with higher rainfall seems to hold only within regions of similar vegetation (grassland or timber).

The fact that the grassland nitrogen relationship can be described by Mitcherlich's logarithmic curve is of theoretical and practical interest, but the physiological certainty remains to be established. It is not impossible that the fixation of nitrogen is governed by Mitcherlich's law. On the other hand, the observation should be mentioned that a similar logarithmic curve can be obtained by plotting the yields of prairie hay per acre of each county against the humidity factors, which points toward the conclusion that soil nitrogen and soil organic matter stand in close relation to the amount of organic matter produced by vegetation. These, however, are merely suggestions and cannot yet be assumed as established.

Summary of the Nitrogen and Organic Matter-Humidity Factor Relation

The study of the nitrogen moisture relationship in temperate and subtropical regions of the United States led to the following observations:

1. The nitrogen-humidity factor relationship is a discontinuous one, consisting of two separate curves, one for grassland soils and one for timber soils.

2. The nitrogen content of grassland soils along an isotherm increases logarithmically with increasing moisture factors. The increase can be expressed mathematically by Mitcherlich's law, giving a differential coefficient of $(\partial N/\partial H)_T = \dfrac{k_2 e^{-k_2 H} N}{1 - e^{-k_2 H}}$

3. The variation of the nitrogen content of originally timbered soils with moisture differs from that of the grassland soils. In the subtropical timber region studied, the nitrogen content does not vary with climatic moisture factors, while in the temperate region an increase of soil nitrogen with increasing humidity factor is indicated.

4. In the temperate region the carbon-nitrogen ratio is approximately constant, namely 11.3, for both timber and prairie soils.

5. The order of importance of factors determining the nitrogen content of soils along the 10°C. isotherm with *great moisture variations* are:

$$\text{Moisture} > \text{Vegetation} > \begin{cases}\text{Topography}\\ \text{Parent Material}\end{cases}$$

where > means "more important than".

THE COMPLETE NITROGEN-CLIMATE RELATIONSHIP

In the introductory statement on page 6 the climate was split up into a temperature factor and a moisture factor. Since the separate influence of the two variables has been established quantitatively in the foregoing chapters, the combined effect of temperature and moisture is now easily found by mere computation[25].

Computation of the Complete Nitrogen-Climate Relationship

Remembering the total differential equation:

$$dN = \left(\frac{\partial N}{\partial T}\right)_H dT + \left(\frac{\partial N}{\partial H}\right)_T dH \qquad \text{(III)}$$

we can replace the general partial differential coefficients $(\partial N/\partial T)_H$ and $(\partial N/\partial H)_T$ by the specific coefficients XXIII and XXIX which gives:

$$dN = -k_1 N dT + \frac{k_2 e^{-k_2 H} N}{1 - e^{-k_2 H}} dH \qquad \text{(XXXIII)}$$

After dividing the entire equation by N, the integration of

$$\int \frac{dN}{N} = -k_1 \int dT + k_2 \int \frac{e^{-k_2 H}}{1 - e^{-k_2 H}} dH \qquad \text{(XXXIV)}$$

can be performed at sight. Assuming that k_1 and k_2 are absolute constants, the integrated equation takes the form:

$$\log_e N = -k_1 T + \log_e (1 - e^{-k_2 H}) + c \qquad \text{(XXXV)}$$

or

$$N = Ce^{-k_1 T}(1 - e^{-k_2 H}) \qquad \text{(XXXVI)}$$

Since this equation is entirely an empirical one, the observational limits for $T = 0° - 22°$, and $H = 0 - 400$ should be constantly kept in mind. The formula holds only for loamy grassland soils, for clay soils or sandy soils some correctional terms would be necessary. No attempt has been made to obtain a nitrogen-climate function for timber soils, since the available nitrogen analyses of timber soils are not yet numerous enough to justify the proposal of a definite mathematical formula.

The equation gives the following information regarding the occurrence of soil nitrogen:

1. If $H = 0$ also $N = 0$, or in other words, in desert regions the nitrogen content of the soil tends to be very low, no matter whether the deserts lie in the arctics or in the tropics.

2. With an increasing humidity factor, soil nitrogen *increases* logarithmically. The rate of increase is greatest in northern regions (Canada) and smallest in southern regions (Texas).

3. With increasing temperature, soil nitrogen *decreases* exponentially. The rate of decrease is greatest in humid regions and smallest in arid regions. Southern regions have less nitrogen in the soil than northern regions, provided equal moisture districts are compared.

As to the numerical magnitudes of the constants, the following experimental values were obtained:

Regions	Humidity factor (N. S. Q.)	k_1	Temperature	k_2
Semi-arid	125-250	0.073	------------	------
Semi-humid	280-380	0.095	------------	------
Humid	300-420	0.101	------------	------
Temperate	------	-----	10.6°-11.7°C.	0.0034
Subtropical	------	-----	17.8°-20.0°C.	0.0073

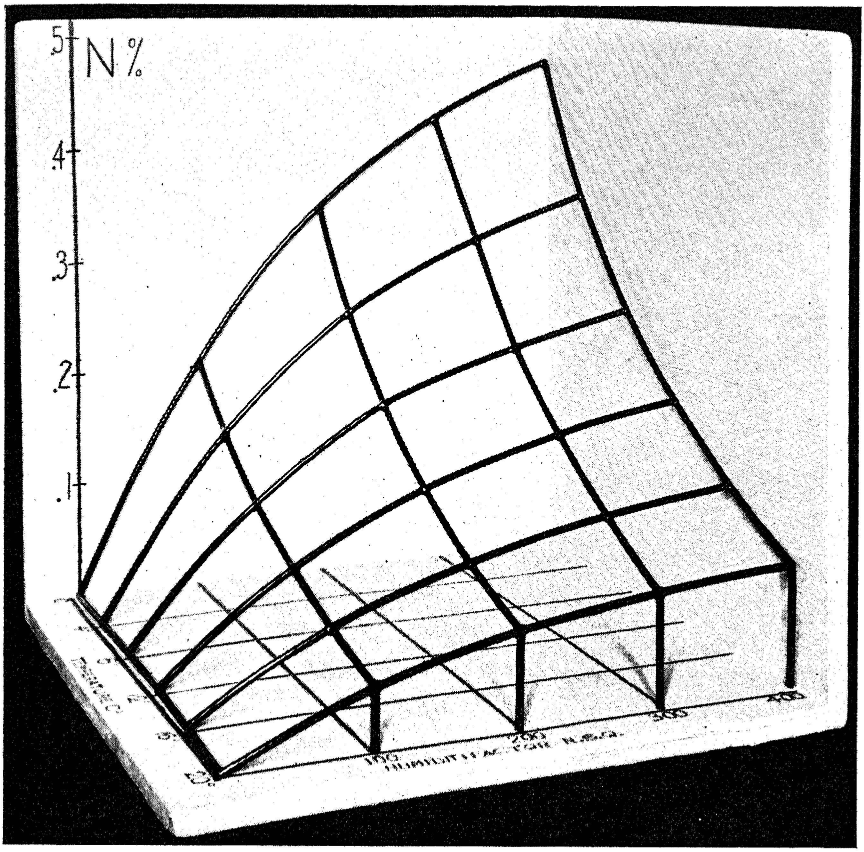

Fig. 22. The nitrogen content of loamy grassland soils in the United States as a function of annual temperature and annual humidity factor (N. S. Q.). The curves express the approximate idealized trend of soil nitrogen of large areas.

On account of a certain heterogeneity of the analytical material, some arbitrary selection in choosing the constants cannot be avoided. The following values satisfy the equation for a *first approximation:*

$$k_1 = 0.08$$
$$k_2 = 0.005$$
$$C = 0.55$$

Equation (XXXVI) then takes the form:

$$N = 0.55e^{-0.08T}(1 - e^{-0.005H}) \qquad \text{(XXXVII)}$$

A comparison between calculated and observed average soil nitrogen values is given in Table 25, and the corresponding nitrogen plane is shown in the three dimensional graph of Figure 22.

TABLE 25.—OBSERVED AND CALCULATED VALUES OF THE SOILS NITROGEN-TEMPERATURE-HUMIDITY FACTOR-EQUATION

Annual temperature C.°	Annual humidity factor (N. S. Q.)	Average total nitrogen content of soil (per cent)		Regions
		Observed	Calculated	
0.0	350	0.47	0.45	Southcentral Canada (Saskatchewan, Manitoba)
2.2	200	0.29 ±0.050[1]	0.29	Southwest Saskatchewan and Northwestern North Dakota
	380	0.34 ±0.017	0.38	Southeast Saskatchewan and Northeastern North Dakota
4.4	220	0.24 ±0.015	0.26	Southwestern North Dakota
	350	0.30 ±0.017	0.32	Southeastern North Dakota
5.6	380	0.27 ±0.018	0.30	West central Minnesota
6.7	350	0.27 ±0.012	0.27	South central Minnesota
	420	0.30 ±0.028	0.29	West central Wisconsin
7.8	420	0.26 ±0.011	0.26	Southwest Wisconsin
8.9	320	0.21 ±0.014	0.21	Northwestern Iowa
	380	0.28 ±0.016	0.23	Northern Illinois
10.0	230	0.19 ±0.012	0.17	South central Nebraska
	350	0.17 ±0.005	0.20	Southern Iowa
11.0	75	0.08 ±0.009	0.07	Southeastern Colorado
	125	0.11 ±0.007	0.11	East central Colorado and Northwestern Kansas
	275	0.20 ±0.005	0.17	Northeastern Kansas and Northwestern Missouri
	325	0.19 ±0.005	0.18	Northcentral Missouri
	375	0.22 ±0.008	0.19	Central Illinois
13.3	350	0.16 ±0.020	0.16	Southern Illinois
14.4	150	0.09 ±0.006	0.09	Texas Panhandle
16.7	350	0.12 ±0.016	0.12	Northern Mississippi
19.0	150	0.08 ±0.007	0.06	Central Texas
	250	0.095 ±0.006	0.08	Eastern Texas
	350	0.10 ±0.006	0.10	Central Mississippi
22.2	200	0.075 ±0.004	0.06	Southern Texas

[1]Mean error.

Although this investigation is based on more than 1000 soil nitrogen analyses, equation (XXXVII) must not be considered as final. From certain large areas no nitrogen analyses could be secured (e. g. Oklahoma, South Dakota) and in general the number of analyses from arid regions is too small to determine accurately the magnitude of the constant k_2. One should also remember that equation XXXIV was integrated on the assumption that k_1 and k_2 are absolute constants. It is quite possible that, in refining equation XXXIII, a variation of the constants themselves may occur.

Nevertheless, the agreement between calculated and observed data indicates that equation XXXVII is satisfactory for a *first approximation* of the specific *idealized* nitrogen-climate relationship of loamy grassland soils in the United States.*

Discussions of the Soil Nitrogen Climate Relationship

A striking result of the present investigation is undoubtedly the isolation of climate as the outstanding factor which controls the nitrogen level of loamy soils within the United States as a whole. Vegetation is the next important factor; topography and parent material probably come in the third and fourth places, the exact order of rank not yet being established definitely. Within large areas, age of the soil seems to be a relatively unimportant factor in the soil nitrogen climate equilibrium.

One may raise the question as to whether or not the nitrogen climate relationship holds in other countries also. Judging from the trend of the nitrogen temperature curves in the United States, one would expect that cultivated tropical soils are low in nitrogen and organic matter. Observations and soil analyses dealing with this question are conflicting. Certain investigators (for instance J. C. Mohr) maintain, that well aeriated tropical soils contain very little or no organic matter, while others (for instance J. Harrassowitz) speak of distinct accumulation of raw humus. Unless a great number of nitrogen data, collected under comparable conditions is available, nothing definite can be said about the validity of the nitrogen climate relation in tropical soils.

A brief survey of nitrogen analyses from the soils of Russia, Norway, Denmark, Switzerland, Italy and Palestine indicates that the general trend of the soil nitrogen climate relationship in Europe does not seem to contradict the results obtained in the United States. However, the amount of data at hand is too small to warrant further comments on this subject.

*It is to be remembered that in formula XXXVI N. S. Quotients are used as moisture indices. Other moisture values would give somewhat different formulas. With rainfall values, for instance, the decrease in nitrogen with rise in temperature would be more pronounced.

Summary

1. Within regions of *constant moisture condition* the nitrogen and organic matter content of soils of medium texture decrease exponentially from north to south in relation to *temperature*. As a rule it can be said, that for every fall of 10°C. in annual temperature, the average soil nitrogen and organic matter content increases 2-3 times. This holds for both timber and grassland soils.

2. Within regions of *constant temperature*, the nitrogen and organic matter content of grassland soils increases logarithmically with increasing *humidity frctors*. The rate of increase is greater in northern than in southern regions. The nitrogen content of originally timbered soils shows little correlation with climatic moisture values.

3. It is possible to combine the nitrogen temperature-and the nitrogen moisture relation of grassland soils into a nitrogen climate function.

4. The order of importance of soil forming factors, in influencing the nitrogen level of loamy soils within the United States, as a whole, is as follows:

$$\text{Climate} > \text{Vegetation} > \left\{\begin{matrix}\text{Topography} \\ \text{Parent Material}\end{matrix}\right. > \text{Age}$$

PRACTICAL ASPECTS OF THE NITROGEN CLIMATE RELATIONSHIP

Nitrogen Turnover.—Before the lands are plowed there is a natural equilibrium between the production of organic matter by vegetation and its decomposition by microorganisms, the balance between these two being determined to a great extent by climatic conditions. Cultivation disturbs that natural equilibrium and decreases the nitrogen content of the soil. This loss of nitrogen was measured by Snyder[69], Alway[51], Shutt[65], and others, and is about 20-40% of the virgin nitrogen for a cultivated period of 20-40 years in the wheat-growing regions of the Great Plains. A simultaneous decrease of fertility is demonstrated by the rapidly decreasing yields of untreated experiment plots.

Often the idea is expressed that nitrogen and organic matter should be restored to the virgin level by adding sufficient amounts of green manure and stable manure. In several publications a nitrogen content of 0.250 to .300 per cent nitrogen is given as a desirable value for a very fertile soil. These figures correspond to the nitrogen content of the very best Minnesota, Iowa, and northern Illinois prairie soils.

Concerning this problem of increasing the nitrogen content of the soil by green manuring and similar methods, the nitrogen climate-relationship leads to the following suggestions. It seems to be possible to build up the nitrogen content of cultivated soils in the North by adding organic material because the low temperature would favor its preservation. The experiments of Snyder in Minnesota[69] and Shutt in Canada[65] tend to support this conclusion. In southern latitudes, however, it will be rather difficult, if not impossible, to increase permanently and profitably the nitrogen content of cultivated soils to the forementioned level by such practices because the high temperature militates against organic nitrogen accumulation by favoring decomposition. As a matter of fact, experiments at the Tennessee Experiment Station and also at the Missouri Experiment Station (unpublished data) have failed to secure any considerable increase in soil nitrogen. Even as far north as Wooster, Ohio (mean annual temperature 49°F.) it has not been possible to reach the original nitrogen content of the unbroken soil.[54]

Recently the term "nitrogen turn-over" has been suggested, a term which refers to the amount of nitrogen that may be supplied to crops from rotation to rotation by means of crop residues, green manures, farm manures, and commercial manures.[39] "It seems probable that in the southern two-thirds of the United States at least, crop production will be maintained or increased by a control of this nitrogen turnover rather than by an attempt to maintain the total nitrogen content at a particularly high level.[1])"

CORRELATION BETWEEN CORN YIELDS AND NITROGEN-CLIMATE FUNCTION

Looking at the various nitrogen-temperature curves of Figure 17, with their pronounced downward trend, the question may arise: *Since nitrogen, which is an outstanding factor in soil fertility, decreases rapidly from north to south, should not the crop yields per acre also diminish from north to south?* This interesting and vital question was investigated for the corn crop (Zea Mays). Only a concise summary of the study will be given here.

The Variation of Corn Yields per Acre From North to South.—The so-called semi-humid region was selected for this study, including the states: eastern North Dakota[55], Minnesota[44], Iowa[18], Missouri[46], Arkansas[2], and Louisiana[35]. In this region the nitrogen temperature relation holds for upland, terrace, and bottom soils, and for prairie and timber soils as well. Moreover, variations of altitude and topography for the entire region are small and do not materially affect crop growth.

Similar to the nitrogen-temperature graphs (Figure 17), a corn yield-temperature diagram was constructed. The 10-year averages (for Arkansas only 7-year and for Louisiana only 5-year county averages were available) of the corn yields per acre for each county of the states mentioned were computed, taking the years 1917-1926. For the same counties the average summer and annual temperatures were either taken directly from climatological tables[75] or estimated from surrounding stations. Plotting the average corn yield of the county against its annual temperature, (Figure 23) clearly demonstrates that the corn yields vary with latitude. *In northern latitudes, the yields increase with increasing annual temperature, while in southern latitudes they decrease.* The maximum of the curve occurs in north-central Iowa.

1. Communication by Professor M. F. Miller.

TABLE 26.—ANNUAL TEMPERATURE AND CORN YIELD PER ACRE

Temperature F.°	Temperature C.°	State	Number of counties	Average corn yields per acre (lowland counties) excluded)	Number of counties	Average corn yield per acre. Lowland counties
36	2.22	North Dakota	7	27.34±0.775	--	------------
38	3.33	North Dakota, Minnesota	12	28.00±1.145	--	------------
40	4.44	North Dakota, Minnesota	11	29.04±0.929	--	------------
42	5.56	North Dakota, Minnesota, Iowa	21	32.22±0.586	--	------------
44	6.67	Minnesota, Iowa	53	37.59±0.473	--	------------
46	7.78	Minnesota, Iowa	19	40.20±0.485	--	------------
48	8.89	Iowa	44	40.95±0.469	--	------------
50	10.00	Iowa, Missouri	23	37.61±0.896	--	------------
52	11.11	Iowa, Missouri	24	32.36±0.603	--	------------
54	12.22	Missouri	40	28.21±0.660	--	------------
56	13.33	Missouri, Arkansas	34	24.82±0.631	3	30.40±2.693
58	14.44	Missouri, Arkansas	18	20.36±0.583	3	29.7 ±2.499
60	15.56	Missouri, Arkansas	20	17.10±0.409	5	27.46±1.073
62	16.67	Arkansas	26	15.88±0.400	--	------------
64	17.78	Arkansas, Louisiana	18	13.52±0.455	3	17.86±1.299
66	18.89	Louisiana	4	13.70±0.645	11	18.07±0.519
68	20.00	Louisiana	2	15.80±1.05	19	18.50±0.463

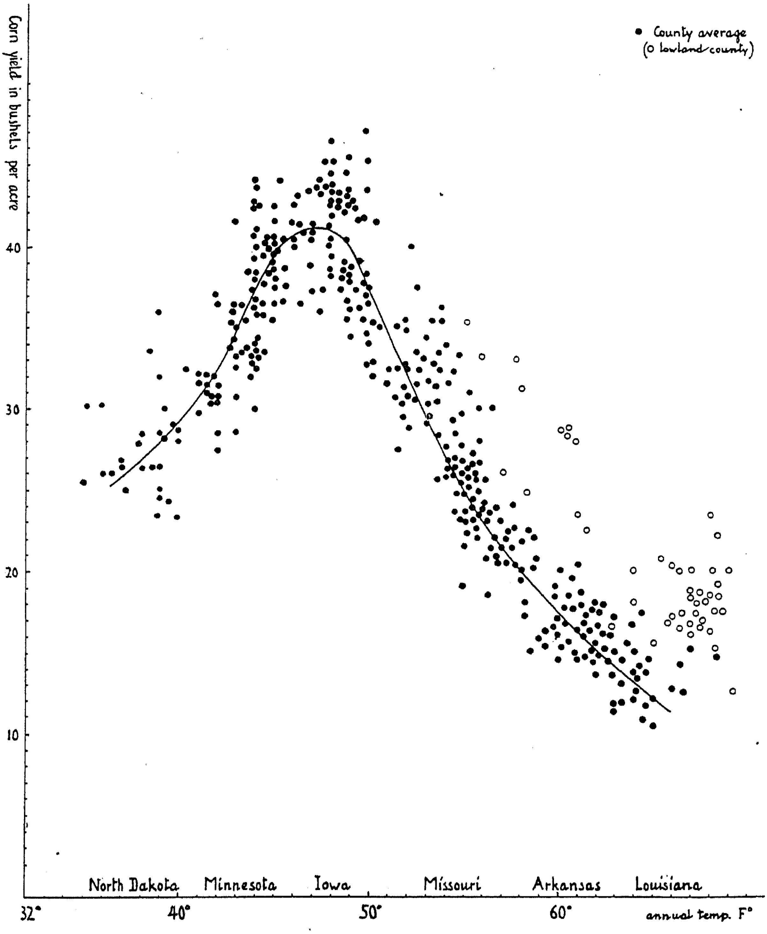

Fig. 23. The corn yield-temperature relationship. Each black point represents the average corn yield per acre of an upland county, while the light points refer to lowland counties. Counties along the Missouri and Mississippi Rivers (light points) have higher corn yields than the corresponding upland counties (black points); but the downward trend is manifested in both cases.

Of particular interest is the descending branch of the corn yield curve (southern Iowa, Missouri, Arkansas, Louisiana). Can this decrease of corn yield per acre be linked up satisfactorily with the *soil nitrogen-climate relation*, or is it more probable that the low yields in the South are due to unfavorable weather conditions (moisture or temperature) or to differences in farming practices? After a detailed study of these four factors involved, the following conclusions were reached:

1. *The role of moisture in determining the corn yield.*—The precipitation during the four months following corn planting increases regularly from north to south, from 11.40 inches in eastern North Dakota to 21.00 inches in

southern Louisiana (see Column 3, Table 27). Since a rainfall of 10-18 inches is considered to be favorable for a 50 bushel corn crop, according to the investigations of Montgomery[47], Kisselbach[28], King[31], Wallace[83], and others[13, 41,67,77,86], moisture conditions in the extreme south (20 inches) compare favorably with those of the leading state of Iowa (16 inches). However, on account of the high temperature of the subtropical regions which stimulates transpiration and evaporation, it is advisable to compare the moisture conditions on the basis of the precipitation-evaporation ratio rather than on rainfall alone.

The columns of Table 27 showing rainfactors and Livingston's[24] precipitation-evaporation ratios indicate that all states (except North Dakota) have practically the same magnitude of moisture indexes. Both in Louisiana and in Iowa, the rainfactor average of the four months following corn planting lies between 20-22. Also the seasonal distribution is about the same for the entire region. This similarity leads to the conclusion that in *normal years* the amount of *rainfall cannot be the sole cause* responsible for the peculiar shape of the corn yield curve.

2. *Temperature affecting corn growth.*—Wallace and Bressman[83] point out that the optimal temperature for the growth of corn is about 90°F., when sufficient moisture is present. Iowa's summer temperature is only 71°F., that of Louisiana is somewhat higher, 78-90°F. Provided that moisture is not a limiting factor, the corn plant, as a rule, responds favorably to higher temperatures, especially in the early stages of growth and before tasseling[12,83]. It seems logical, therefore, to assume that the *ascending* branch of the corn yield curve from North Dakota to Iowa is due to beneficial effects of heat upon growth of corn. But no good physiological temperature reason is found to explain the rapid and continuous decrease of the corn yields south of Iowa.

Wallace[82] calls attention to the statistical observation that under temperatures above normal, the corn yields in the Corn Belt tend to decrease which has been explained by Hessling[13] on the basis of shortage in water (drought). Undoubtedly in hot periods July and August moisture may easily become the limiting factor in southern regions, but the fact that the normal precipitation-evaporation ratio is about equal throughout the region, suggests that in *normal* years, southern yields do not need to be so much lower than those of Iowa, as judged from *temperature conditions alone*.[1]

3. *Influence of farming systems on corn yields.*—It is generally believed that in the United States the southern type of farmer is not as efficient as the northern type. As a matter of fact corn yields in the South have remained about steady during the last fifty years, while in northern states, especially in Iowa and Minnesota, the corn yields have decidedly increased, which probably can be attributed to improvement of corn varieties and soil management[84].

1. No exact data on sunshine influences on corn growth covering wide areas are available and the possible effect of wind influences has not yet been investigated on a large scale.

Table 27.—Summary of Climatological Data

Region	Season	Total rainfall in 4 summer months (inches)	Total rain factor in 4 summer months	Rainfall-evaporation ratio. (June-Aug.)	Average summer temperature for 3 months F.°	
Eastern North Dakota	May	11.40	17.88	0.86	65.1	
S. W. Minnesota	June	14.91	21.13	0.97	68.3	
S. E. Minnesota	July	15.06	21.92	0.88	69.1	
Western Iowa	August	16.54	21.28	----	71.9	
Central Iowa		15.98	20.52	0.80	72.1	
Eastern Iowa		16.16	21.28	0.70	70.9	
North Missouri		17.32	20.12	----	75.2	
South Missouri		17.35	19.60	0.83	76.1	
North Arkansas	April	17.84	22.37	0.77	77.9	74.5
South Arkansas	May	17.99	21.02	----	79.8	76.5
North Louisiana	June	17.90	19.80	0.67	81.1	78.2
South Louisiana	July	21.08	21.68	1.46	81.3	79.1

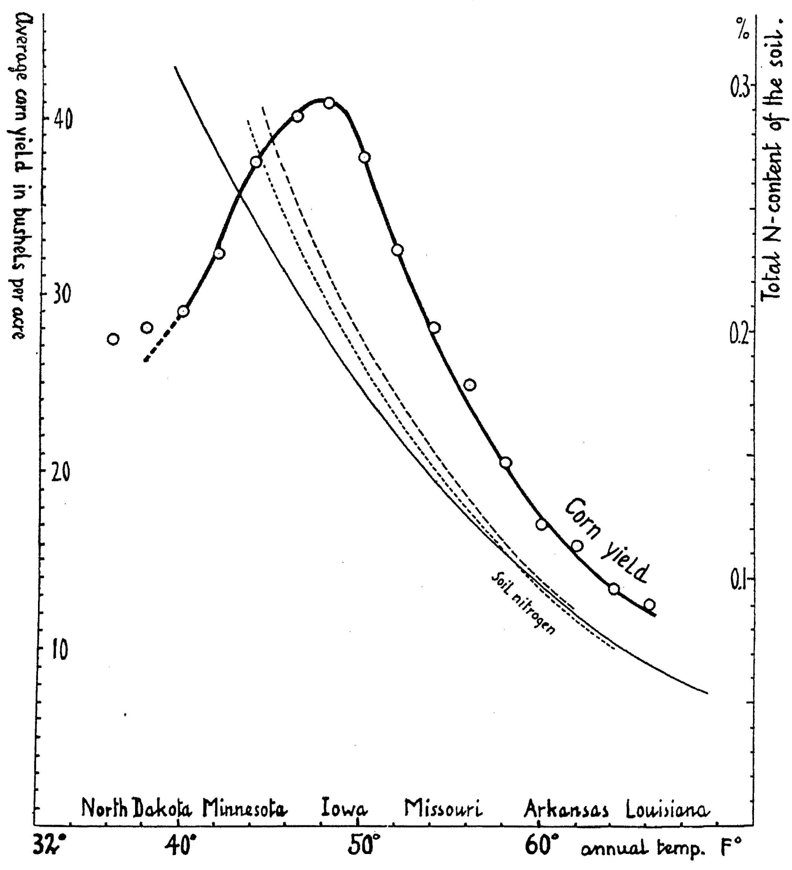

Fig. 24. Average corn yield per acre and average soil nitrogen as a function of annual temperature.

On the other hand, one should not forget that in the South the best land usually is occupied by cotton, rather than by corn, which might also contribute to the great difference in corn yields between northern and southern states.

Experiments show that the addition of fertilizers to the soil will remarkably increase the corn yield in the South, which points toward the conclusion tion that in such cases not the climate or the type of farmer but the poorer soils are mainly responsible for the low yields. An inspection of the earliest corn records[76] show clearly that southern corn yields were always lower than northern ones. If it were possible to construct an earlier, detailed corn yield-temperature curve, the maximum would be somewhat lower than that in Figure 23, but nevertheless, the descending branch would be typical.

4. *Corn yields and soil nitrogen.*—The view that not only weather but also soil properties are mainly responsible for the low corn yields in the South was expressed by Wallace and Bressman[83] in 1923: "The cotton states would undoubtedly be another corn belt if the soil were only richer. As it is, nearly all the records of corn yielding over 200 bushels per acre have come from the South, such results being obtained by planting corn thickly on land heavily fertilized."

There are three established lines of evidence in favor of a soil nitrogen-corn yield relation. *First*, the average corn yields decrease uniformly and exponentially from north to south, beginning with central Iowa, independently of age and origin of the soil, but in close relation to temperature as does soil nitrogen. *Second*, the corn yields in the South can be increased appreciably by green manuring with legumes or by application of nitrogen fertilizers[10,59]. *Third*, fertilization without nitrogen will not result in large crop yields[9].

TABLE 28.—RELATION OF AVERAGE CORN YIELD AND AVERAGE SOIL NITROGEN

States	Average total nitrogen content of soil in % (Upland loams and silt loams)	Average county corn yields in bushels per acre		Difference	
		Observed	Calculated	+	−
Louisiana	0.067	13.70	11.739	1.961	-----
Louisiana	0.076	13.52	13.761	-----	0.241
Arkansas	0.086	15.88	16.006	-----	0.126
Arkansas	0.098	17.10	18.701	-----	0.160
Arkansas, Mo.	0.110	20.36	21.396	-----	1.036
Missouri	0.124	24.82	24.530	0.280	-----
Missouri	0.140	28.21	28.134	0.076	-----
Mo., Iowa	0.160	32.36	32.625	-----	0.265
Mo., Iowa	0.177	37.61	36.443	1.167	-----
Iowa	0.198	40.95	41.159	-----	0.209
				3,484	3,478

The decided parallelism between nitrogen content of the soil and corn yield per acre is clearly seen in Figure 24, where the average soil nitrogen curves and the average corn yield curve are compared. South of central Iowa both nitrogen and corn yields decrease uniformly and exponentially, within the corn belt as well as within the cotton belt. No sudden break exists, not even at the boundary of glaciation where one might expect it.

North of central Iowa the cool climate apparently overwhelms the beneficial effect of higher soil fertility (nitrogen) and the yields decrease.

Plotting the average corn yields against average total nitrogen content of soil (upland loams) as is done in Figure 25, and Table 28 results in a straight line from Louisiana to Iowa. The corn yield-soil nitrogen relation is almost perfect. The equation of the curve has the form

$$C = 224.58N - 3.307^{*} \qquad \text{(XXXVIII)}$$

where C means average corn yields per acre in bushels and N, average total nitrogen content of the soil.

*The correlation coefficient has a value of +0.995.

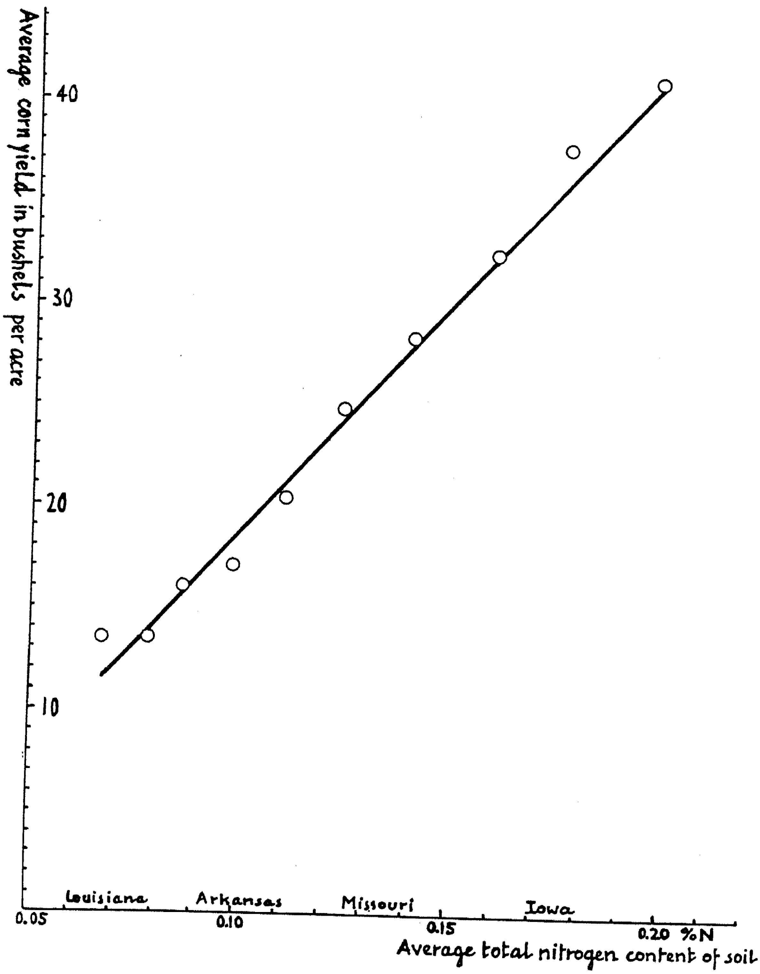

Fig. 25. The average corn yield per acre in relation to the average total nitrogen content of the soil.

Discussion of the Soil Nitrogen-Corn Yield Relationship

Although the correlation between average soil nitrogen and average corn yield south of Iowa is nearly perfect ($r = +0.995$), the conclusion does not necessarily follow that the former is the cause of the latter since other variables of unknown magnitudes are involved. The following reasoning seems to be justified. It has been customary to attribute the low corn yields in subtropical regions mainly to weather influence or to improper methods of farming, but in the light of this study, the nitrogen-temperature relation deserves equal consideration. Climate exerts a double action upon the southern corn yields.

Directly, it may have an unfavorable effect upon the corn plant itself; indirectly, it is responsible for the low content of nitrogen and organic matter in the soil which in consequence may influence the magnitude of the corn yield. No attempt has been made to state the exact order of importance of the various factors discussed. This significant problem is beyond the scope of the present investigation.

It might be well to keep in mind that this entire investigation is based on average corn yields as well as average amounts of soil nitrogen and, therefore, the conclusions reached apply only to the average conditions of large regions. Single selected corn fields and soil types is likely to behave quite differently from the above averages, yet this does not weaken the general significance of the results obtained.

GENERAL SUMMARY

1. Difficulties encountered in the maintenance of nitrogen and organic matter in Missouri soils led to the study of climate as a possible factor controlling the nitrogen level in soils.

2. Climatic maps have been constructed which show annual isotherms and annual isonotides (precipitation-evaporation ratio, rain-factor, N. S. Quotient)

3. Statistical correlation between annual temperature and average soil nitrogen and organic matter content mainly of cultivated soils revealed the following facts:

   a. Within regions of similar moisture conditions the nitrogen and organic matter content of upland, terrace and first bottom land soils, including both prairie and timber vegetation, decreases from north to south.

   b. Mathematically speaking, the trend of the decrease can be represented by a negative exponential function.

   c. Speaking in general terms, it may be said that for each fall of 10°C. in annual temperature, the average nitrogen and organic matter content of soils increases two to three times.

   d. Within the Great Plains area the carbon-nitrogen ratio seems to become somewhat wider with decreasing temperature.

4. Statistical correlation between moisture and soil nitrogen, within regions of constant temperature, led to the following conclusions:

   a. The nitrogen content of cultivated grassland soils located along an isotherm, increases logarithmically with increasing moisture factors. The increase can be expressed mathematically by Mitscherlich's law.

   b. The average nitrogen content of originally timbered soils located along an isotherm shows little variation between the range of humidity factors studied, namely N. S. Q. 100-400.

5. It is possible to combine the nitrogen-temperature and the nitrogen-moisture relation of grassland soils of the United States into a nitrogen-climate function.

6. The order of importance of soil forming factors in influencing the nitrogen level of medium textured soils within the United States as a whole is indicated as follows:

$$\text{Climate} > \text{Vegetation} > \left\{\begin{matrix}\text{Topography}\\ \text{Parent Material}\end{matrix}\right. > \text{Age}$$

The position of the cultivation factor in the above series is not known.

7. Practical aspects of the nitrogen-climate relationship:

a. The importance of the nitrogen temperature relation and the so-called "nitrogen-turnover" has been discussed.

b. It is shown that the average corn yield decreases from north to south (beginning with northern Iowa) as does the average nitrogen content of the soil. It is suggested that the nitrogen and organic matter temperature relationship is one of the principal causes of the low corn yields in the South.

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ERRATA

Formula XIX on Page 33 should read $O.M. = 6.50e^{-0.104T_{8^\circ}^{20^\circ}}$

Formula XXI on Page 37 should read $(N)_H = Ce^{-k_1 T_{0^\circ}^{22^\circ}}$

Table reference in last line on Page 44 should read Table 22 instead of 21.

Table reference in 9th line on Page 45 should read Table 21 instead of 22.