RELATIONSHIPS BETWEEN NITROGEN FERTILIZATION, SOIL MOISTURE, AND YIELD OF CROPS

by

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INTRODUCTION

Agricultural practice and experience over the centuries and many years of recent experimental work in different parts of the world have demonstrated that nutrition and moisture conditions materially affect crop yields. In general, adequate plant nutrition may be obtained with modern inorganic fertilizers, but water supply is limited in many areas. Growing populations all over the world point sharply to the need for better use of limited water resources, especially in semi-arid and arid regions, to produce food and fiber. Fertilizers, when needed, are excellent tools for increasing productivity, and they may contribute to better water use. Unfortunately available information is not sufficiently complete to advise indiscriminate use of fertilizers. Most experiments conducted in arid or semi-arid areas have considered either the fertility variable (nutrient deficiencies, dose, time of application) or the moisture variable (amount of water required, time of irrigation application, etc.), but both factors have not been studied together.

It was the purpose of this paper to review experiments which primarily combined nitrogen fertilization treatments with known amounts of water use when applied to common small grains and row crops.

LITERATURE REVIEW

As stated previously, research information dealing with nitrogen-moisture interactions still is rather incomplete. Efforts have been made to determine optimum rates of fertilizer for use in humid or sub-humid areas, where water supply is a lesser problem. In arid or semi-arid regions, experimental work has dealt mostly with such water conservation practices as mulches, strip cropping, and contour cultivation systems. A study of both factors seems to be expensive and time consuming. Soil moisture determination is a long and tedious operation which is hampered by several factors such as sampling procedures, equipment use, and human factors. Certainly, equipment actually available to determine soil moisture has improved continuously since tensiometers, gypsum blocks, and neutron meters have been used, but still a field determination should be considered only a "best approximation".

Many farmers and irrigation technicians have had the impression that when fertilizers are used water requirements are greatly increased, because crop yields are larger, and that using a higher plant population required more irrigation water. The question is not new, as might be supposed. Research was begun in 1850 by Sir J. Lawes at Rothamsted, England, and it has been continued to the present time. This review was arbitrarily divided into two different periods: the old time experiments, called "early experiments", most of them done using pot culture methods, and the "modern experiments" mostly performed in the field and occasionally associated with greenhouse experiments.

Early Experiments

Briggs and Shantz (2) made a comprehensive review of experiments up to

1913 dealing with fertilizer action upon water requirements. They defined "water requirement" as the ratio of the weight of water absorbed by plants during the total period of growth to the weight of dry matter produced during the same period. Most of these experiments have only historic value, because in many cases fertilizer treatments were not comparative and gave rather confusing results. Briggs and Shantz reviewed twenty-three experiments but nitrogen carriers were used only in the following:

Author	Date	Fertilizer Treatments
Lawes	1850	Manure-Ammoniacal & Mineral Manure
Hellriegel	1883	$C_a (NO_3)_2$ and Potash
Dehérain	1892	Manure - N - P - K
King	1894	Manure - KNO_3
Liebscher	1895	N - P - K
Von Seelhorst	1899	N - P - K
Wilforth & Wimmer	1902	$K - N_a - N$
Von Seelhorst & Bünger	1907	$N - P - K - C_a$
Ohlmer	1908	$N - P - K - C_a$
Preul	1908	$K - N_a - N$
Wimmer	1908	K - N
Widtsoe	1909	N - P - K
Leather	1910; 1911	N - P - K
Montgomery & Kiesselbach	1912	Manure
Pfeiffer, Black & Flügel	1912	N

Briggs and Shantz concluded that, almost without exception, the experiments cited showed a reduction in water requirement accompanying the use of fertilizers. In highly productive soils this reduction amounted to only a small percentage. In poor soils the water requirement may be reduced one-half or even two-thirds by the addition of fertilizers.

Early work at Idaho done by Neidig and Snyder (15) using pot techniques showed a similar tendency. They included several variables in their experiment; the most important were three levels of moisture and two levels of nitrogen. They also studied the effect of split nitrogen applications and soil moisture fluctuations during the wheat plant cycle. The moisture treatments were 25 percent (moisture equivalent value), 20 percent, and 15 percent.

They maintained the preestablished moisture conditions by carefully weighing the pots and adding the required amount of water at frequent intervals. Only two nitrogen rates, 0 and 200 pounds per acre of N_aNO_3 were used. According to the writer's opinion, this is the weakest point of the experiment because a response curve can be more precisely drawn when more points are plotted on it. A uniform application of P, K, and lime was also made. Results were as follows:

Table 1. Grain and straw yields (grams) and increased yields (percent)

	Grain yields (g.) at:			Straw yields (g.) at:		
% Moisture Levels	25% (100%ME)	20% (80%ME)	15% (60%ME)	25% (100%ME)	20% (80%ME)	15% (60%ME)
Check pots	4.57	2.83	2.97	8.5	7.0	6.3
200 lbs/A N_aNO_3	13.63	10.47	9.80	27.6	20.4	16.4
% increase	298	369	329	324	291	260

Data showed that grain and straw yields increased when nitrogen was added. The highest grain yield was obtained at the highest moisture level with nitrogen fertilization. However, the largest yield increase (369 percent) was obtained with the second moisture level. Also, nitrogen fertilization gave the highest straw yield. The straw-grain ratio for fertilized treatments did not change significantly (2.02 for M.E. conditions and 1.94 for 80 percent M.E.). It means that the second level of moisture proportionally produced more grain than straw. Singh and Mehta (23) attempted to determine a quantitative relationship between water requirement and soil fertility at Benares, India. Variability in soil fertility was induced by the applications of different manures and chemical fertilizers. Fertilizer materials were carefully sieved and mixed with a typical loam soil. Care was taken to ensure that the organic manures had decomposed before Pusa seed wheat was planted.

Table 2. Yield and water requirements of Pusa wheat as affected by fertilizer materials.

Treatments	Transpiration per plant (Kg.)	Yield per plant (g.)	Water Requirement
Check	4.078	3.141	1,497.4 (1)
$(NH_4)_2SO_4+K_2SO_4$ and basal dressing of Crotalaria juncea	7.712	4.864	1,585.5
Castor cake	6.351	5.027	1,263.7
Crotalaria juncea	6.613	5.083	1,301.0
$(NH_4)_2SO_4 + K_2SO_4$	7.809	5.238	1,490.9
Farm yard manure	6.939	5.312	1,276.5 (1)
Superphosphate + K_2SO_4	6.556	6.007	1,091.4
Superphosphate + $(NH_4)_2SO_4$	10.320	9.695	1,064.4

(1) These values appear to be in error.

Data showed a linear inverse correlation between the water requirement and yield per plant and a linear positive correlation between transpiration per plant and yield per plant. Unfortunately, they did not report any adequate statistical interpretation. In summary, fertilization reduced the quantity of water needed per unit of dry matter production (more efficient water use). However, the total quantity of water transpired by the crop was increased. It should be noted that they calculate "water requirement" according to the Briggs and Shantz concept which is entirely different from evapotranspiration values more commonly used by modern workers.

Modern Experiments

Early work at Nephi, Utah, was done by Peterson (20) during the period 1942 - 1950. This work showed the effect of rainfall on nitrogen response with wheat.

Table 3. Rainfall distribution (inches) and wheat grain yield increases (bu/A)

	Rainfall (inches)		Grain yield (bu/A)		
Crop year	Spring(1)	Annual	Check	40-0-0(2)	Increase
1943	4.52	12.42	20.3	27.6	7.3
1944	6.66	16.17	20.4	33.6	13.2
1945	4.43	16.75	22.3	29.5	7.2
1946	3.78	18.84	11.7	17.3	5.6
1947	4.23	15.09	35.3	43.1	7.8
1948	3.25	11.11	28.0	30.3	2.3
1949	4.15	12.68	17.4	22.8	5.4
1950	2.01	10.39	28.8	35.6	6.8
					$\bar{X}$ = 6.95

(1) April; May; June; (2) N_aNO_3

Grain yields always were increased by nitrogen fertilization. Rainfall undoubtedly influenced yield of wheat and response to nitrogen. Correlation coefficients were as follows:

Table 4. Correlation coefficients between rainfall distribution and yields

	Yields of:	
Rainfall period	Check	Fertilized
Spring	-.3675	.7443
Annual	-.5504	.4139

Data indicated good positive correlation between spring rainfall and yield with nitrogen fertilization. Information would be more accurate if available water in the soil at planting time were known.

The effect of nitrogen and phosphorus fertilizers and irrigation on sorghum yields was studied during 1951 by Painter and Leamer (18) in an experiment with two moisture levels and several doses of nitrogen and phosphorus. "Wet" plots were maintained at a soil moisture tension below 0.7 atmospheres throughout the growing season. "Dry" plots were plots where soil moisture tension reached 12-15 atmospheres except during leaching when tension was maintained below 0.7 atmospheres. Data obtained were summarized as follows:

Table 5. Mean yield of grain sorghum (bu/A) of N - P treatments at two moisture levels.

	Checks	60-0-0 lbs/A	60-80-0 lbs/A	120-80-0 lbs/A	240-80-0 lbs/A	Average lbs/A
"Wet" plots	40.4	61.4	69.5	77.1	92.5	68.2
"Dry" plots	42.6	56.2	63.5	74.2	74.2	62.1

The lowest yields were associated with the no treatment plots. When phosphorus and moisture were not limited, yields followed Mitscherlich curve patterns. The statistical analysis is given in table 6.

Table 6. Least square differences for moisture, fertility and moisture x fertility interaction

L.S.D.	Moisture	Fertility	Moisture x Fertility
1%	4.29	6.17	8.71
5%	2.99	4.65	6.56

These data indicated that yield increases, as a result of more frequent irrigation, were not obtained unless nitrogen was applied, or conversely, fertilizers were more effective in increasing sorghum yields when the crop was supplied with enough water.

Hanks and Tanner conducted experiments during 1949 and 1950 with several crops and fertilizers at Hancock, Wisconsin, on a Plainfield sandy soil (8). Corn data obtained in 1950 show more efficient water use associated with the use of nitrogen fertilizer.

Table 7. Water-use efficiency increase (percent) by corn

Crop and Year	Water supplied during growth period		Fertilizers		Water use efficiency (bu/A-inch)	Increase (%)
	Rainfall (in.)	Irrigation (in.)	N (lbs/A)	Manure (Ton/A)		
Corn - 1950	12.5	5	25	9	3.87)	156
	12.5	5	0	9	2.46)	100
	12.5	0	17	6	3.57)	163
	12.5	0	0	6	2.18)	100

Water use efficiency was improved nearly 60 percent when a high fertility level was used.

The first large scale field experiments were probably conducted by Zubriski and Norum (27) at several Branch Experiment Stations in North Dakota during the period 1952-54. They worked with fallowed and non-fallowed soils, knowing from previous experience that phosphorus was needed in both cases but nitrogen only in non-fallowed lands. The following table summarizes several of their tests with wheat on non-fallowed land fertilized with 100 pounds of 22-24-0 per acre.

Table 8. Water-use efficiency increase (percent) on fertilized wheat, non-fallowed lands.

Experimental site location	Yield of wheat, bu/A		Total soil moisture after harvest (in/A)		Water-use efficiency (bu/in)		% Increase
	Check	Fertilized	Check	Fertilized	Check	Fertilized	
Dickinson 1953	10.7	16.2	4.7	4.0	2.27	4.05	+78
Williston 1953	8.9	13.5	3.2	3.4	2.77	3.97	+43
Langdon 1954	34.5	44.1	16.3	18.7	2.11	2.35	+11
Edgeley 1954	9.7	17.0	17.6	17.7	0.55	0.96	+74
Minot 1954	14.6	18.9	10.6	9.0	1.37	2.10	+53
Hettinger 1954	8.3	10.7	1.3	1.9	6.38	5.10	-20
Dickinson 1954	12.1	14.4	6.5	6.5	1.86	2.21	+18
Williston 1954	6.1	7.0	2.5	2.5	2.44	2.80	+14

Available moisture was determined with moisture blocks at approximately weekly intervals during the growing season. Water use efficiency was calculated by the author using Viets' (26) formula.

It is apparent from data shown above that in the majority of these trials the moisture remaining in the soil profile after harvest was about the same in the fertilized and non-fertilized plots. Slight differences can be attributed to experimental error in moisture determinations. Fertilizers did however advance the maturity of wheat which resulted in corresponding earlier withdrawals of moisture from the profile. They concluded if there is sufficient moisture in the soil at seeding time appropriate fertilization should be used on soils believed to be deficient in available nutrients.

Some data reported by the South Dakota Agricultural Experimental Station in 1954 (9) show very clearly the effect of nitrogen and moisture. Two sources of nitrogen and two moisture conditions were studied in an irrigated rotation trial.

Table 9. Effect of irrigation, rotation and nitrogen fertilization on wheat yield, (bu/A) Redfield, 1949-1953

Treatment	Irrigated rotations			Non-irrigated rotations		
	4-year C-W-A-A	2-year C-W	% increase for alfalfa	4-year C-W-A-A	2-year C-W	% increase for alfalfa
None	22.4	20.1	11.4	20.4	14.9	36.9
Nitrogen fertilization(1)	33.9	32.8	3.3	25.6	22.6	13.3
% increase due to fertilization	51.3	63.1	---	25.5	51.6	---

(1) Nitrogen rates were 30 lbs/A and 60 lbs/A on non-irrigated and irrigated plots, respectively..

Data indicated that nitrogen fertilizer had more effect on yields than rotation or irrigation. However, the effect of nitrogen fertilizer was greater in the irrigated than in the non-irrigated rotations. Nitrogen increased wheat yields more in non-legume rotations, both irrigated and non-irrigated, than in legume rotations. Under the experimental conditions studied the nitrogen fertilizer-irrigated combination gave larger increases in yield than any other treatment. Statistical treatment was not given to support these conclusions.

Another comparison of moisture-nitrogen interaction can be made from a research study conducted simultaneously under field and greenhouse conditions by Mann (12) at Kansas State University, Manhattan. Differences in wheat varieties used permit comparison on a relative basis, only. He studied changes in plant characteristics of Pawnee wheat as affected by fertilization and moisture during 1953 and 1954, using several fertilizer treatments but no moisture variables.

Table 10. Grain yield (bu/A) of fertilized wheat, Manhattan, Kansas

Year	Check	N	P	K	NP	NPK
1953	25.47	24.03	27.64	26.25	27.00	28.59
1954	32.54	32.06	34.49	30.24	49.23	51.22

L.S.D. ($P = 0.05$) = 3.78

Yields in 1954 were all larger than in 1953, due no doubt, to the different rainfall conditions. During the crop year July 1952 to June 1953 precipitation amounted to 20.16 inches as compared with 25.33 inches in 1953-54. Available soil moisture data were not recorded. Taking the years individually, there were no significant differences in 1953 except that nitrogen applied alone depressed grain yields. In 1954 nitrogen alone did not improve yields, but the nitrogen + phosphorus treatment gave significant increases over the check. The nitrogen + phosphorus + potassium treatments were not significantly greater than the nitrogen + phosphorus combination. In summary, nitrogen effect was largely conditioned by rainfall. When precipitation was moderated (1954), a nitrogen response associated with phosphorus was obtained. Using similar soils but a different wheat (Pusa 52X Federation) in a greehouse experiment with three different moisture levels, grain yields per plant were as follows:

Table 11. Grain yields per plant (grams)

Moisture	Check	N(1)	P(2)	K(3)	NP	NPK
High (80% F.C.)	3.23	5.15	3.71	3.69	7.48	6.01
Medium (50% F.C.)	3.73	3.84	4.73	2.41	5.71	6.07
Low (20% F.C.)	2.29	2.21	3.18	1.76	2.93	3.27

L.S.D. ($P = 0.05$) = 0.92

(1) = 120 lbs/A; (2) P_2O_5 = 180 lbs/A; (3) K_2O = 120 lbs/A

Moisture x treatment interaction was highly significant. Under high moisture level, N, NP, and NPK treatments significantly increased yields over the check. Under medium moisture conditions the nitrogen treatment was not effective; phosphorus showed to increase its efficiency under these conditions. Nitrogen + phosphorus and nitrogen + phosphorus + potassium treatments gave significant responses.

Under low moisture conditions only phosphorus and nitrogen + phosphorus + potassium treatments significantly increased yields. Moisture alone increased yields; the best level corresponded to medium conditions. The effect of nitrogen and nitrogen + phosphorus treatments increased with increase in moisture level, and phosphorus was more effective at medium moisture levels than at high levels.

In dry eastern Washington (10-15 inches of annual precipitation) moisture and nitrogen govern wheat production according to Leggett (10). Most of the rainfall occurs during late fall, winter and early spring. Therefore, a large amount of the water used by crops must be stored in the soil during the wet season. The amount stored depends on:

1) Amount of rainfall received
2) The rainfall fraction that enters into the soil
3) Water-holding characteristics of the soil

Maximum yields depend upon both efficient use of the entire supply of available moisture and presence of an adequate supply of all essential nutrients. Numerous fertility experiments conducted throughout the area over a period of several years indicated that the use of nitrogen fertilizers generally increased wheat yields. This was attributed to the fact that soil organic matter did not release enough available nitrogen to enable the crop to use the available moisture supply. The results of ninety wheat fertilization experiments were used to determine the relationships between moisture and wheat yield. Fifty-seven of the experiments were conducted on fallowed land and thirty-three under annual cropping. Results were summarized by the writer as follows:

Table 12. Yields (bu/A) and water-use efficiency for fallow

Rainfall Characteristics	Average Inches moisture avail. to the crop			Average Wheat yields (bu/A)		Average Increase	Water-use efficiency fertilized
Area	From soil	From rain	TOTAL	Fertilized	Checks	ease	plots(bu/A-in.)
Less than 10"	6.9	2.2	9.1	25.9	20.0	5.9	2.84
10" - 15"	7.7	2.9	10.6	38.9	31.9	7.0	3.67
More than 15"	10.3	3.0	13.3	56.2	40.8	15.4	4.22

Table 13. Yields (bu/A) and water-use efficiency for annual cropping

Rainfall Characteristics	Average Inches moisture avail. to the crop			Average Wheat yields (bu/A)		Average Increase	Water-use efficiency fertilized
Area	From soil	From rain	TOTAL	Fertilized	Checks	ease	plots(bu/A-in.)
Less than 15"	4.9	2.8	7.7	20.3	6.6	13.7	2.63
More than 15"	8.0	3.9	11.9	45.1	24.9	20.2	3.78

Several conclusions were drawn from these data:

a) Nitrogen fertilization improved yields in all cases, even under drought

b) Water-use efficiency was increased with fertilization

c) Fallowing proved to be a more efficient method of management than annual cropping

Leggett also correlated maximum yields (fertilized plots) with available soil moisture (soil moisture plus rainfall); he obtained a close correlation ($r = .87$) and the regression line adjusted with the linear regression technique was:

$$Y = 5.8\ (S.M. + R) - 23.8$$

Where Y = yield, bu/A and (S.M. + R) = available soil moisture. This equation indicated that four inches of water are required to produce any grain and 5.8 bu. of wheat per acre was produced for each additional inch of available water. Further analysis indicated that the correlation coefficient obtained using the (S.M. + R) expression was higher than those obtained using either as a separate variable.

A few experiments have been conducted with corn to evaluate the nitrogen fertilization-soil moisture relationship. One experiment was conducted by Carlson et al. (3) on a Gardena loam soil in North Dakota in an area which receives about fifteen inches of annual rainfall. The experiment had a split-plot design, with moisture levels as main plots. Water was applied to the irrigated treatment section when soil moisture in the top two feet approached 50 percent of the available water. Each main non-irrigated plot received four nitrogen rates (0- 30 - 60 - 120 pounds per acre of N as NH_4NO_3) and two different plant densities. The same treatments were used on the irrigated plots, but with different doses (0 - 60 - 120 - 180 pounds per acre of N). Phosphorus fertilizer was used each year at the uniform rate of 100 pounds per acre of P_2O_5. Evapotranspiration was calculated by successive moisture determinations.

Table 14. Water-use efficiency by corn under irrigated and non-irrigated conditions

	Non-irrigated			Irrigated		
Treatment	Evapotransp. (in.)	Dry matter (lbs/A)	Water use efficiency (lbs/A-in.)	Evapotransp. (in.)	Dry matter (lbs/A)	Water use efficiency (lbs/A-in.)
			1956			
A	10.82	6,560	606	13.91	5,870	422
B	11.11	7,330	660	14.81	9,330	630
C	10.57	7,170	678	15.56	6,870	442
D	10.97	7,240	660	13.77	10,630	772
			1957			
A	10.03	5,060	504	16.89	6,780	401
B	10.39	5,950	573	18.38	9,110	496
C	10.14	5,950	587	19.40	8,300	428
D	9.82	5,860	597	16.53	10,900	659

Treatments were as follows:
A = 0 lbs N/A; 14,000 plants/A in 1956; 10,000 plants/A in 1957
B = 120 lbs N/A; 14,000 plants/A in 1956; 10,000 plants/A in 1957
C = 0 lbs. N/A; 23,000 plants/A in 1956; 20,000 plants /A in 1957
D = 120 lbs N/A; 23,000 plants/A in 1956; 20,000 plants/A in 1957

In the non-irrigated treatments neither plant density nor nitrogen fertilizer greatly influenced water use efficiency although the least efficient water use occurred in unfertilized plots at low plant density. At both nitrogen rates and plant densities, the amount of dry matter produced per inch of water used in evapotranspiration was higher in non-irrigated plots than in the irrigated plots, except at the 120 pounds per acre rate at the high plant population level. In irrigated treatments, nitrogen fertilizer increased water use efficiency at both plant densities and years. The largest increase was obtained with the high plant population level.

Evans et al (4) reported data from a two-year experiment with sweet corn on an alluvial soil (Chehalis loam) in Oregon.

Table 15. Effects of nitrogen on unhusked graded yields (T./A) for different moisture treatments

N (lbs/A)	Year: 1954. Yields (T./A)				Year: 1955. Yields (T./A)			
	M_1	M_2	M_3	M_4	M_1	M_2	M_3	M_4
50	5.0	5.5	5.3	4	6.1	5.7	6.0	4.9
100	6.5	5.4	5.7	4	8.2	5.7	7.3	5.1
200	6.8	5.7	7.3	4	8.2	6.0	7.5	5.6

All plots received 50 pounds per acre of 11 - 48 - 0 at planting time. NH_4NO_3 was applied at a later date to complete the pre-established rate. Moisture treatments were as follows:

M_1: Irrigated at low soil moisture tensions: approximately one atmosphere.
M_2: Irrigated at high soil moisture tensions: approximately twelve to fifteen atmospheres until tasseling of the corn; then low tensions until harvest.
M_3: Irrigated at low soil moisture tensions: approximately one atmosphere until tassel time; then high tensions: approximately fifteen atmospheres until harvest.
M_4: Irrigated at high soil moisture tensions: approximately twelve to fifteen atmospheres uniformly throughout the growth season.

The significant interaction between moisture and nitrogen emphasizes that for maximum efficiency both water and nitrogen must be at a high level, that is, when nitrogen was applied at a high rate, the effect of added moisture was more pronounced. Conversely, when moisture was maintained at a high level, nitrogen effects were more pronounced.

Indian workers have contributed in this field. Gautam (6) at Bichpuri at Agra, India, reported in 1961 data collected during the 1946-47 period. He designed a split-plot experiment, with two levels of irrigation (60,000 and 90,000 gallons per acre) and two sources of nitrogen (farm compost and $(NH_4)_2SO_4$) applied at three rates (0, 30, and 60 pounds of N per acre). The crop studied was wheat and data were summarized by the writer as follows:

Table 16. Total dry matter (lbs/A) as influenced by irrigation levels and N doses and sources

Total dry matter (lbs/A)	Levels of irrigation (gals/A)		N sources		N doses (lbs/A)		
	60,000	90,000	Compost	$(NH_4)_2SO_4$	0	30	60
	3312	2808	2712	4168	2600	3224	3664
C.D. at 5%(1)	Non signif.		328		328		

(1) Called "Critical Difference", a coefficient similar to the L.S.D.

Conclusions were as follows: 1) The 60,000 gallons per acre irrigation level was adequate to meet the moisture requirement, since the higher level decreased yields. 2) The optimum nitrogen level was perhaps between 30 and 60 pounds per acre. However, a higher level of nitrogen had to be included to determine the highest possible yield under irrigation and fertilization. 3) Inorganic fertilizer $(NH_4)_2SO_4$ proved to be a more efficient source of nitrogen than compost. Some criticisms concerning this experiment were: 1) The experiment was conducted during a short period of time. 2) Available soil water supplied was not reported.

Several workers have reviewed plant characteristic changes induced by crop fertilization (12). They have reported root weight increase and subsequently a deeper water extraction. However, in a few cases observations were made to determine the efficiency of water use.

Linscot et al (11) studied corn root distribution and root activity in a Thurman loamy sand soil characterized by low water holding capacity and high bulk density due to close packing of the sand grains. This soil was fertilized with 0 and 140 pounds of N per acre as NH_4NO_3 and two moisture levels. A uniform application of phosphorus and magnesium was made. After irrigating the profile to a depth of eight feet, a plastic black cover was placed over one-half of each plot to separate evapotranspiration from transpiration effects. In other words, ground cover prevented gain or loss of moisture except by transpiration during the last 60 days of the growing season.

Nitrogen fertilization apparently affected the seasonal use of water by corn. Nitrogen fertilized corn, growing on both covered and uncovered plots used considerably more water during the period 40 to 65 days after planting than did corn which received no nitrogen fertilizer, but this difference diminished toward maturity. The same situation was observed with root extension development. Corn growing on all covered plots removed approximately nine inches of water (transpiration) during the season. Uncovered soil, growing corn with and without application of nitrogen lost 10.5 and 10.0 inches of water, respectively, (evapotranspiration) during the same period of time.

Table 17. Water-use efficiency and relative efficiency for check and fertilized plots

	Soil Uncovered			Soil Covered		
Plots	Yield (bu/A)	Water use efficiency (bu/A-in.)	Relative efficiency	Yield (bu/A)	Water use efficiency (bu/A-in.)	Relative efficiency
140 lbsN/A	50	4.7	1.38(1)	39	4.3	1.38(2)
No N	34	3.4		28	3.1	

(1) 4.7/3.4; (2) 4.3/3.1

Nitrogen fertilized corn was approximately 1.4 times as efficient in the use of water for grain production in both covered and uncovered plots as corn which received no nitrogen fertilizer. It was concluded that good nitrogen nutrition, which resulted in increased root production, increased subsequent moisture utilization during a critical period of plant development prior to and during tasseling, and so resulted in higher yields.

Viets is probably the author who has done the most intensive work in this field, reviewing and interpreting data available from other authors and considering different crops. In 1960 (7) he summarized data from several experiments as follows:

Table 18. Yields of crops and water-use efficiency as influenced by fertilization.

Crop	Location	Year	Treatment (lbsN/A)	Evapotranspiration (inches)	Yield (lbs/A)	Water use efficiency (lbs/A-in.)
Corn	N.Platte, Nebraska	1956	0	10.5	2,060	196
			80	11.4	3,370	295
Winter Wheat	N.Platte, Nebraska	1956	0	8.7	278	32
			40	8.7	296	34
			80	8.7	287	33
Grain Sorghum	Bushland, Texas	1958	0	21.0	3,444	164
			120	22.3	7,000	317
			240	22.9	7,374	322

Corn and wheat crops were grown under limited moisture supply, but grain sorghum was grown under irrigation. However, when corn was supplied with a minimum amount of available water, nitrogen was able to increase water use efficiency 50 percent. When very little water was stored at planting time, the use of nitrogen did not result in increase water use efficiency by winter wheat. Grain sorghum was grown in a nitrogen deficient soil; hence, with enough available moisture, nitrogen response and water use efficiency increased sharply up to 120 pounds per acre of nitrogen.

Later, in 1962, Viets (26) reviewed the moisture-fertilization relationship more extensively. Some examples are cited. Viets reported that Cassady grew Plainsman milo in paraffin coated, ten-gallon cans filled with Dalhart fine sandy loam that was fertilized with phosphorus and potash and placed outdoors in Las Cruces, New Mexico. Irrigation was applied when moisture tension reached 750 cm of water. A series of nitrogen applications (NH_4NO_3) was made.

Table 19. Yields (g/can) and water-use efficiency for Plainsman fertilized milo

N applied (lbs/A)	Total plant yield (g./can)	Evapotranspiration (in./can)	Water use efficiency (g./in.)
0	No crop	12.54	---
0	22.4	30.68	0.73
100	62.0	36.70	1.69
200	102.5	42.10	2.43
300	157.5	51.53	3.06
400	208.9	60.28	3.46
500	240.4	65.68	3.66
600	310.2	69.71	4.45
700	325.9	74.96	4.35
800	353.9	78.49	4.51
900	355.2	78.49	4.52
940	351.9	78.49	4.48

In this case, water use efficiency was a hyperbolic function of yield. Another example was obtained from data collected by Jensen and Sletten in Bushland, Texas (26). Hybrid grain sorghum RS-610 was grown at two moisture levels and three nitrogen levels.

Table 20. Effects of nitrogen fertilization on fertilized and irrigated grain sorghum

	Moisture treatments					
	M_1 = Preplanting irrigation only			M_4 = Preplanting irrigation + complementary irrigation		
Nitrogen (lbsN/A)	Yield (lbs/A)	Evapotr. (in.)	Water-use eff. (lbs/acre-in)	Yield (lbs/A)	Evapotr. (in.)	Water-use effic. (lbs/acre-in)
0	2979	14.8	201	3442	21.0	164
120	2626	15.4	171	6964	22.3	312
240	2430	14.8	164	7232	22.9	316

Rainfall from planting to harvest was 11.30 inches. This amount of rainfall was not sufficient to meet the needs of the crop without irrigation. Another example was obtained from trials conducted also by Jensen and Sletten (26) at the same place, but using Concho winter wheat.

Table 21. Effect of nitrogen fertilization on fertilized and irrigated wheat

		Moisture Treatment					
		Preplanting irrigation only			Preplant.irrig.+complem.irrig.		
Year	N (lbs/A)	Yield (bu/A)	Evapotr. (in)	Water-use eff. (bu/acre-in)	Yield (bu/A)	Evapotr. (in)	Water-use eff. (bu/acre-in)
1956	0	16.9	19.4	0.87	33.6	23.6	1.42
dry	80	18.1	19.7	0.92	45.9	30.4	1.51
year	120	17.5	20.3	0.85	52.4	30.2	1.74
1957	0	27.1	17.1	1.58	28.8	24.1	1.20
norm.	120	42.3	18.1	2.34	52.5	28.4	1.85
year	180	44.4	17.3	2.57	48.9	27.4	1.78
1958	0	20.2	18.4	1.10	26.3	26.6	0.99
wet	120	33.9	19.4	1.75	49.8	27.0	1.84
year	180	26.7	19.1	1.40	38.2	26.2	1.46

Nitrogen fertilization significantly increased both yields and evapotranspiration rates. Water use efficiency was increased by fertilization. In the wet year (1958) fertilization increased yields but had little effect on evapotranspiration. In both 1957 and 1958, use of 180 pounds of nitrogen, as compared to the 120 pound rate, decreased yields and water use efficiency because of lodging. In all three years, nitrogen fertilization increased the efficiency of water use.

Working at North Platte, Nebraska on a Holbrege very fine sandy loam soil during the three year period 1954-56, Ramig and Rhoades (21) reached similar conclusions. The experimental design used was a split plot, with moisture levels as the major plots and nitrogen applications as the subplots. Water was applied before seeding time to establish four levels of moisture in the six-foot soil profile; they were 0, 2.9, 5.9, and 8.1 inches of available water. Precipitation received during the growing season (October 1 - June 20) was below average in two out of three years. Each moisture treatment was split into eight nitrogen treatments to study doses and method of application. Results were summarized as follows:

Table 22. Grain yields (bu/A) and straw yields (T/A) of wheat crop as influenced by nitrogen fertilization and available moisture.

Available	lbs. N/A				lbs. N/A			
moisture	0	20	40	80	0	20	40	80
(inches)	Grain yields (bu/A)				Straw yields (bu/A)			
0	7	10	9	8	.37	.60	.70	.75
2.9	15	21	25	25	.58	.89	1.18	1.38
5.9	19	28	32	37	.78	1.20	1.45	1.87
8.1	20	29	35	39	.85	1.24	1.58	1.90

There were highly significant effects of preplanting soil moisture level, rate of nitrogen application, and the interaction of these variables on yields of grain and straw during each of the three years; however, split applications of fertilizer did not give significant differences.

Yield data were fitted with multiple regression equations. Seventy to 85 percent of the variation in grain yield was accounted for by moisture level and fertilization rate. In contrast, only 32 to 59 percent of the variation in wheat straw yields could be accounted for by these factors. Moisture data collected indicated that the wheat crop removed more water when nitrogen fertilizer was applied. Nitrogen stimulated greater plant and root development and the roots probably more thoroughly permeated the soil volume. When there was no preplanting moisture, water extraction from the soil was equal for both nitrogen fertilized and nonfertilized plots. The ratio of yield to total water use, an index of efficiency of water use, increased as preplanting available soil moisture and rate of nitrogen fertilization increased.

Table 23. Water-use efficiency of wheat (bu/A-in) as influenced by nitrogen fertilization and available moisture

N fertilizer (lbsN/A)	Water use efficiency (bu/A-in)				
	Available water (inches)				
	0	2.9	5.9	8.1	Mean
0	.62	.98	1.22	1.12	0.98
20	.83	1.35	1.68	1.55	1.35
40	.71	1.62	1.87	1.82	1.50
80	.61	1.56	2.04	1.94	1.54
Mean	.69	1.38	1.70	1.61	

However, no further increase in water use efficiency occurred when preplanting available soil moisture exceeded 5.9 inches. There were variable effects of nitrogen fertilization on the efficient use of water with different levels of preplanting moisture. Water use efficiency decreased as the rate of nitrogen fertilization increased above 20 pounds per acre under conditions of low preplanting soil moisture. In contrast, water use efficiency increased with increased rates of nitrogen fertilization at the higher soil moisture levels.

An experiment conducted by Ferguson (5) during the 1955-60 period at Brandon, Manitoba, and reported in 1963, allowed him to demonstrate that at least in that area, with 18.2 inches of annual precipitation, summer fallow is not essential for moisture conservation, and, on the contrary, very inefficient water use resulted from frequent summer fallowing. Fertilizers, on the other hand, have increased water use efficiency.

The soil used in the experiment was a sandy loam at the surface, with a gravel layer at about forty-two inches. To a depth of four feet, this soil was found to have a field moisture holding capacity of 6.5 inches.

The yield of wheat grown was computed: a) immediately after summer fallow; b) as second and third crop after summer fallow; c) wheat grown continuously. Each crop was grown with and without fertilization. In fertilized plots, a starter application of 40 pounds per acre of ammonium phosphate (11 - 48 - 0) was used. Also, in (b) and (c) treatments an annual application of 100 pounds per acre of NH_4NO_3 (33 - 0 - 0) was broadcast immediately after seeding.

Table 24. Wheat yields (bu/A) in a fertilized rotation at Brandon, Manitoba.

Crop Sequence	Treatment	1955	1956	1957	1958	1959	1960	5-years mean	Difference
Wheat grown on fallow	Fertilized	40.3	38.8	50.2	33.5	36.4	22.5	36.3	
	Check	38.7	35.6	30.1	24.1	33.2	20.3	28.7	7.6
Wheat grown as second crop	Fertilized		34.8	39.7	32.4	31.5	28.6	33.7	
	Check		17.8	26.8	15.0	22.5	17.7	20.7	13.0
Wheat grown as third crop	Fertilized	(1)	32.8	47.0	26.3	33.0	26.6	33.2	
	Check		11.9	34.8	14.9	16.5	11.6	17.9	15.3
Wheat grown continuously	Fertilized	(1)	32.8	37.3	26.0	26.2	21.8	28.8	
	Check		11.9	22.7	20.0	18.4	12.2	17.0	11.8

(1) Second crop

In general, fertilizers increased wheat yield. A variance analysis of wheat yields showed a significant difference ($P < 0.05$) between fertilized and unfertilized plots each year. The relative yield increase due to fertilizer was greater for wheat grown as second and successive crops after summer fallow than it was for wheat grown on summer fallow. Growing season evapotranspiration by wheat as a third crop was higher when fertilizer was used.

Table 25. Annual and mean evapotranspiration in inches.

Crop sequence	Treatment	Evapotranspiration in inches				
		1956	1957	1958	1959	Mean
Wheat on fallow	Fertilized	12.44	10.94	7.30	8.46	9.79
	Check	13.12	10.81	7.34	8.25	9.93
Wheat as second crop	Fertilized	12.31	11.14	7.33	8.01	9.69
	Check	11.46	11.55	6.84	8.13	9.49
Wheat as third crop	Fertilized	12.00	11.82	7.36	8.17	9.84
	Check	11.27	10.65	7.18	8.00	9.28

This effect was attributed to the fertilizer action on plant growth, since fertilizing almost doubled the yield of third crop wheat. The same trend was found with second crop wheat but not so consistently. Fertilizing did not have as great an effect on the growth of second crop wheat. In all cases, fertilizing increased soil moisture efficiency. The yield of wheat per inch of evapotranspiration was increased primarily because of increased yields rather than decreased evapotranspiration.

Table 26 Annual and mean water-use efficiency (bu/acre-inch) by wheat.

Crop sequence	Treatment	Water-use efficiency (bu/acre-inch)				
		1956	1957	1958	1959	Mean
Wheat on fallow	Fertilized	3.12	4.59	4.59	4.30	4.15
	Check	2.71	2.78	3.28	4.02	3.20
Wheat as second crop	Fertilized	2.83	3.56	4.42	3.93	3.68
	Check	1.55	2.32	2.19	2.77	2.21
Wheat as third crop	Fertilized	2.73	3.98	3.57	4.04	3.58
	Check	1.06	3.27	2.08	2.06	2.12
Mean	Fertilized	2.84	4.04	4.19	4.09	3.80
	Check	1.77	2.79	2.52	2.95	2.51

Working with the effect of the number and timing of irrigations on grain sorghum production, Musick et al (13) found at Garden City, Kansas, that increased yields, due to nitrogen fertilization, were disproportionately greater than the slight increases in seasonal evapotranspiration; therefore, nitrogen increased water use efficiency considerably. Experiments were conducted for a three-year period, 1958-60, on a Chesnut soil, Richfield clay loam, silted phase. They experimented with four irrigation levels and four nitrogen doses:

Irrigation levels

I_1 = Preplanting irrigation only (Early June).
I_2 = Preplanting + 12-16 inch plant height (July 9-25).
I_3 = Preplanting + 12-16 inch plant height + boot stage (August 6-16).
I_4 = Preplanting + 12-16 inch plant height + boot stage + milk stage of grain (August 24 - September 6).

Preplanting irrigation was sufficient to wet the soil to field capacity to a depth of six feet (available water holding capacity is 2.0 inches per foot of depth). Irrigation during the growing season wet the soil to a depth of four feet and required applications of four to six inches of water.

Nitrogen levels: Ammonium nitrate (33.5 percent N) was used at these nitrogen rates: 1) 0 pounds per acre, 2) 40 pounds per acre, 3) 80 pounds per acre, and 4) 120 pounds per acre.

Table 27. Annual and mean water-use efficiency by grain sorghum as modified by nitrogen fertilization.

N applied lbs/A	Yields (lbs/A)					Evapotranspiration (in)					Water-use efficiency (lbs/A-in)				
	1958					1958					1958				
	I_1	I_2	I_3	I_4	Mean	I_1	I_2	I_3	I_4	Mean	I_1	I_2	I_3	I_4	Mean
0	6,104	5,643	6,292	5,633	5,918	19.23	20.21	21.22	22.68	20.83	318	280	297	248	286
40	6,177	6,841	6,387	6,242	6,412	19.54	20.06	20.16	21.85	20.40	316	341	317	286	315
80	6,078	6,654	6,680	6,425	6,459	19.87	19.77	20.99	22.13	20.69	306	337	319	290	313
120	6,556	6,774	6,970	6,743	6,761	20.39	20.74	19.80	22.09	20.76	322	328	354	305	327
Mean	6,229	6,478	6,582	6,261	6,387	19.76	20.20	20.54	22.19	20.67	316	321	322	282	310
Stat sign.															
	1959					1959					1959				
0	5,516	6,590	6,428	7,299	6,458	15.91	18.36	20.81	23.22	19.58	347	359	309	314	332
40	7,125	7,912	8,396	7,507	7,735	16.98	19.63	22.56	23.36	20.63	420	403	372	321	379
80	7,189	7,237	8,031	8,227	7,671	16.72	18.97	21.64	22.85	20.04	431	382	371	361	386
120	6,900	7,690	8,228	8,585	7,851	16.88	20.58	23.40	24.76	21.40	409	374	352	348	371
Mean	6,682	7,357	7,771	7,904	7,429	16.62	19.38	22.10	23.55	20.41	402	379	351	336	367
Stat sign.															

Nitrogen fertilization increased seasonal evapotranspiration one to two inches under moderate response conditions in 1959. No significant effect was observed under the low response conditions of 1958.

Maximum efficiency of water use varied considerably among years, but occurred within the range of sixteen to twenty-one inches of seasonal evapotranspiration. The I_3 treatment produced maximum average efficiency of 322 pounds per acre inch when seasonal evapotranspiration was 20.54 inches in 1958. In 1959, I_1 produced maximum average efficiency of 402 pounds per acre inch when seasonal evapotranspiration was only 16.62 inches. Fertilization probably made the difference. However, due to the fact that varieties used in both experiments were not the same, some of this improvement could be due to plant variation.

The same authors reported data of experiments also conducted at Garden City (14) from 1954 to 1959 which show that good irrigation water management and nitrogen fertilization can increase water use efficiency by wheat crops. The soil was a Richfield clay loam, with low fertility in the surface horizon.

Using the Blaney-Criddle method, they calculated the evapotranspiration as follows: $U = K \times F$ where: U = Cumulated consumptive use for the growing season, K = Empirical coefficient for the growing season, and F = Sum of consumptive-use factors for all periods within the growing season.

$$\text{If } K = 0.71 \text{ and } F = 33.84$$
$$U = 0.71 \times 33.84 = 24 \text{ inches}$$

Data was summarized by the writer as follows:

Table 28. Water-use efficiency by wheat (bu/A-inch) as influenced by 4 nitrogen levels and 3 moisture conditions.
Period: 1954-55

Amount of N applied (lbsN/A)	Yield in bu/A			Water-use efficiency (bu/A-in)		
	Moisture treatments			Moisture treatments		
	"Dry"	"Medium	"Wet"	"Dry"	"Medium"	"Wet"
0	37.9	44.6	44.9	1.57	1.85	1.87
50	38.6	46.6	47.8	1.60	1.94	1.99

(cont'd)

Amount of N applied (lbs N/A)	Yield in bu/A			Water-use efficiency (bu/A-in)		
	Moisture treatments			Moisture treatments		
	"Dry"	"Medium"	"Wet"	"Dry"	"Medium"	"Wet"
100	40.6	47.7	48.4	1.69	1.98	2.01
200	40.7	50.1	47.2	1.69	2.08	1.96
			Period: 1957-59			
0	47.9	47.9	50.9	1.99	1.99	2.12
30	50.9	51.4	51.2	2.12	2.14	2.13
60	49.7	50.3	50.7	2.07	2.09	2.11
90	47.0	48.6	50.0	1.95	2.02	2.08
120	48.0	49.3	49.3	2.00	2.05	2.05

Irrigation treatments were as follows: "Dry": Only one irrigation before fall seeding. "Medium": Same as "dry" plus one irrigation at the boot stage. "Wet": Same as "dry" plus three or four spring irrigations.

Data showed that the highest water use efficiency was reached with 30 pounds per acre of N. In general, higher nitrogen rates decreased yields. Irrigation treatment increased water use efficiency in all cases when the level was raised from "dry" to "wet" situations.

Olson et al (16, 17) working in Nebraska, conducted a rather extensive investigation with 121 field experiments during the interval 1960-62. They measured the available moisture throughout the soil profiles during the crop season. Their results are summarized in Table 29.

Table 29. Yield increment (percent) and water-use efficiency increase (percent) as influenced by fertilization on small grains and row crops.

Crops	Yield (bu/A) Ch.N	Fer.	Yield incre. (%)	Water-use effic.(bu/A-in) Ch.N.	Fer.	Water-use efficiency increase	Water-use effic.distribution Row C. Average	Small gr. Average	All crops Average
Corn	77	118	53	5.3	7.6	+43)	35.5		29.7
G.Sorghum	60	82	36	5.3	6.8	+28)			
Oats	46	65	41	3.9	5.1	+35)		24	
Wheat	28	34	21	2.3	2.6	+13)			

(1) Fertilizers used were: For small grain crops: 40 + 13 + 0
(pounds per acre) For row crops: 80 to 160 of N + 9 to 13 of P_2O_5 + 10 of Zn.

Conclusions were that grain crops required, under Nebraska conditions, an average of 29 percent less water for producing each bushel of grain with optimum fertilization. Also fertilization increased the water use efficiency of corn and grain sorghum more than for small grains. This is most likely due to the fact that summer row crops extracted water from greater depths than did small grains, at least under Nebraska conditions.

In his review of fertilizer influence on crop use of water, Viets (26) mentioned situations of increased moisture efficiency with decreasing moisture availability. He also pointed out that maximum water use efficiency by a crop is not especially desirable if more than an economic amount of fertilizer was used in accomplishing that efficiency. Apparently this case was not accomplished here. In the following table, they separated the total set of experiments into two groups, expressed as the driest and wettest locations, according to moisture storage at planting, plus seasonal rainfall.

Table 30. Yield (cwt/A) and extra water used (in) due to fertilization under Nebraska conditions.

Crop	Locations	Yield cwt/A Non fertil.	Yield cwt/A Fertiliz.	Cwt. grain/inch water used Non fertil.	Cwt. grain/inch water used Fertiliz.	Extra water used due to fertil.(in)
Wheat	20 driest	18.5	20.8	1.67	1.73	0.9
	20 wettest	15.3	19.7	1.19	1.45	1.1
Oats	10 driest	14.0	20.0	1.29	1.72	0.7
	10 wettest	15.7	21.8	1.19	1.57	0.8
Corn	16 driest	36.7	58.6	2.86	4.18	0.8
	16 wettest	51.3	74.6	3.13	4.36	0.9
Grain Sorgh.	13 driest	26.1	37.2	2.86	3.66	0.9
	13 wettest	41.7	56.3	3.15	4.04	0.9

Mean values for the 30 driest small grain locations demonstrated greater water use efficiency than for the wettest locations. Grain yields of wheat were better in the drier situations, while those of oats were slightly better with the higher moisture. Corn and grain sorghum, however, yielded strikingly better than the others at the higher moisture levels, and water use efficiency was correspondingly enhanced. The authors also correlated several factors by crops (Table 31). In general, the correlations were poor, being significant only for some of the row crops.

Table 31. Annual and mean correlation coefficients between available moisture and yield of fertilized plots.

		Correlation coefficients (r)				R
Factors	Crops	1960	1961	1962	3 years	3 years
Available moisture at planting vs. yield	Wheat	-.36	-.97	-.07	-.17	
	Oats	-.10	.46	.63	.19	
	Corn	.09	.37	.25	.01	
	G.Sorgh.	.61	.44	.79*	.58*	
Seasonal available moisture vs. yield	Wheat				-.02	
	Oats				.14	
	Corn				.73*	
	G.Sorgh.				.68*	
Total available moisture vs. yield	Wheat					.17
	Oats					.23
	Corn					.76*
	G.Sorgh.					.71*

* = Significant

It seems to be that moisture availability and yield were not closely related during the 1960-62 period for wheat and oats. Perhaps moisture was not a factor limiting yields in most experiments, in which increasing amounts of stored moisture and/or rainfall did not give corresponding yield increases. Presumably, a better correlation could be expected during periods of subnormal rainfall in the area.

Tucker et al (24, 25) reported preliminary conclusions from an experiment conducted at Perkins, Oklahoma, in an area of 34.10 inches of average annual rainfall. They were trying to correlate two levels of moisture with three levels of nitrogen fertilization by wheat crops. Results are available only for 1961-62 and 1962-63.

Table 32. Yields of wheat during the 1961-62 period (33.20 inches of rainfall).

N (lbs/A)	Yield obtained at moisture levels (bu/A) (1)		
	M_1	M_2	Average
0	34.6	46.2	40.4
60	34.1	55.4	44.8
240	21.5	40.8	31.2
Average	30.1	47.5	

(1) The authors did not report what the moisture levels were.

All plots received 120 pounds of 0-90-0 P and 75 pounds per acre of 0-0-50 K prior to seeding. Nitrogen at the 60 pound per acre level increased yields only at the higher level of moisture. The 240 pounds per acre nitrogen rate reduced yields drastically under dryland conditions, and decreased yields slightly in the irrigated plots.

Table 33. Yields of wheat during the 1962-63 period (28.63 inches of rainfall

N (lbs/A)	Yield obtained at moisture levels (bu/A) (1)		
	M_1	M_2	Average
0	21.7	21.0	21.3
60	38.5	50.8	44.7
120	36.7	57.4	47.0
Average	32.3	43.1	

(1) The authors did not report what the moisture levels were.

All plots received 120 pounds per acre of 0-45-0 P and 75 pounds per acre of 0-0-60 K prior to seeding. The 60 and 120 pounds per acre rate of nitrogen increased yields of wheat at both soil moisture levels. The 60 pounds per acre application of nitrogen at the M_1 level out-yielded the 120 pounds per acre application at the same moisture level but the situation was reversed at the M_2 level. At the M_1 moisture level, the best nitrogen level would be around 60 pounds per acre of nitrogen. At the M_2 moisture level, the nitrogen rate would be slightly higher.

DISCUSSION

Black (1) made a clear interpretation of the water-soil fertility interaction. He differentiated two situations: I) when the water supply is ample; II) when it is limited. Black's definition was used as a criteria of interpretation in this report.

Measurements of water utilization in soil culture or irrigated experiments with an ample supply of water have shown, as was explained before, that when the crop yield is increased by raising the soil fertility level, the evapotranspiration usually increases, but the ratio of yield/evapotranspiration increases also; hence water is used more efficiently at high than at low fertility levels.

Viets (26) pointed out that at least six possible situations may exist for evapotranspiration and yield relations when yield is changed by fertilization. Diagrammatic models are shown in figure 1. As it was stated before, two basic assumptions are made: 1) water supply is ample; 2) soils are needing nitrogen fertilization.

Model A is obtained when evapotranspiration and yield increase linearly. When yield is zero, evapotranspiration is also zero. There is no increase in water use efficiency with increase in yield through fertilization.

Model B is obtained when evapotranspiration and yield increase linearly, but when yield is zero, evapotranspiration has a positive value. Most experiments discussed before fit into this model, according to figures 2, 3, and 4.

Model C corresponds to the case when evapotranspiration is independent of yield. Water use efficiency increases linearly when yield increases. Probably this model is not commonly found.

Model D indicates that evapotranspiration is independent of yield when

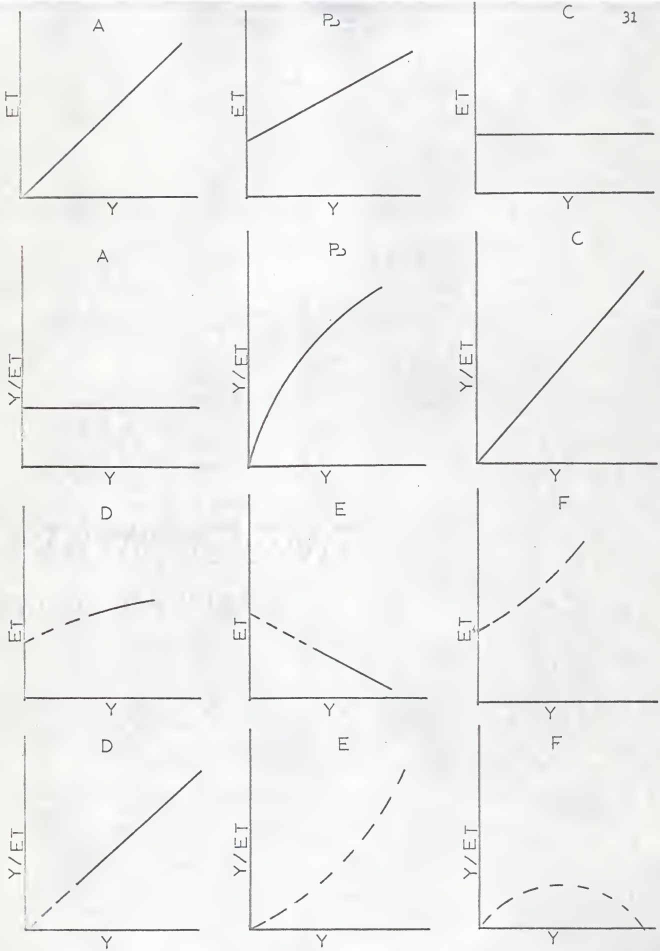

Fig 1 Possible models of the relation between evapotranspiration (ET) and yield (Y) and water-use efficiency (Y/ET) vs. yield.

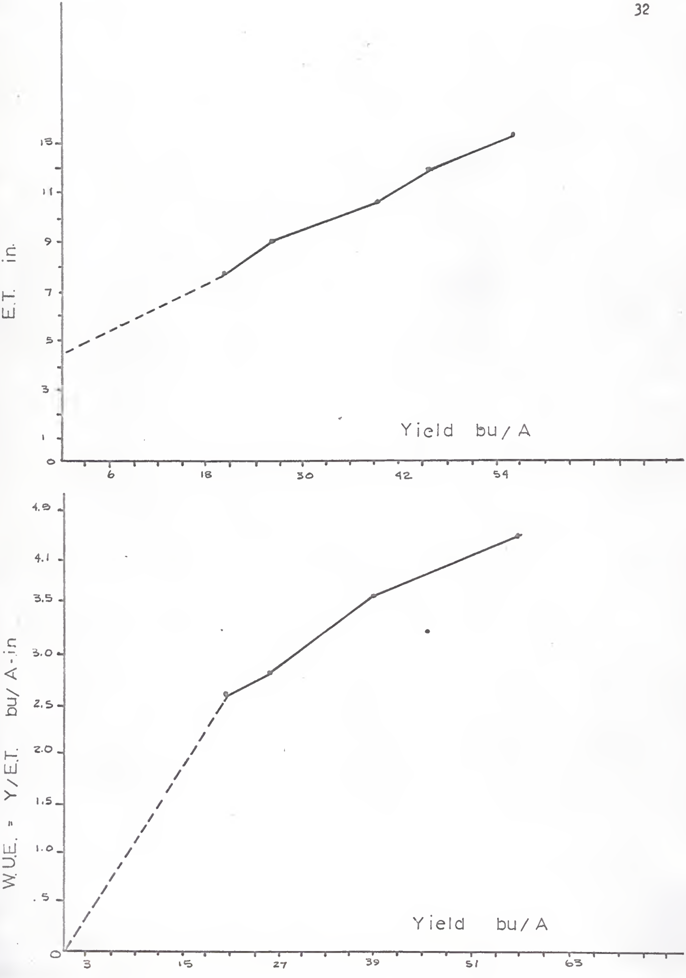

Fig 2 Data obtained from Table 12

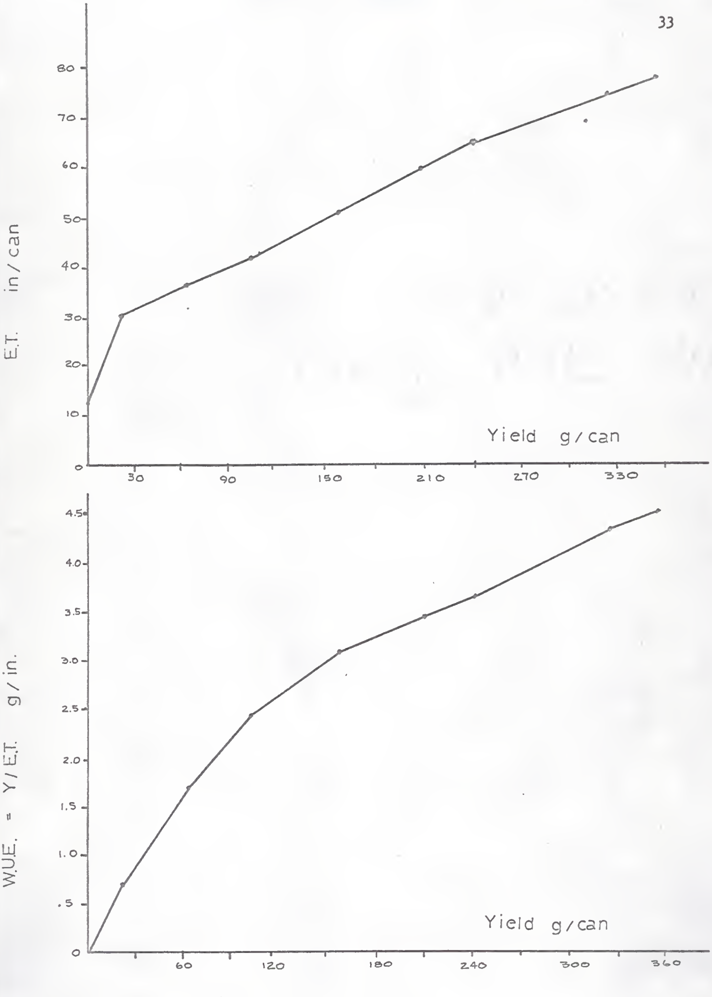

Fig 3 Data obtained from Table 19

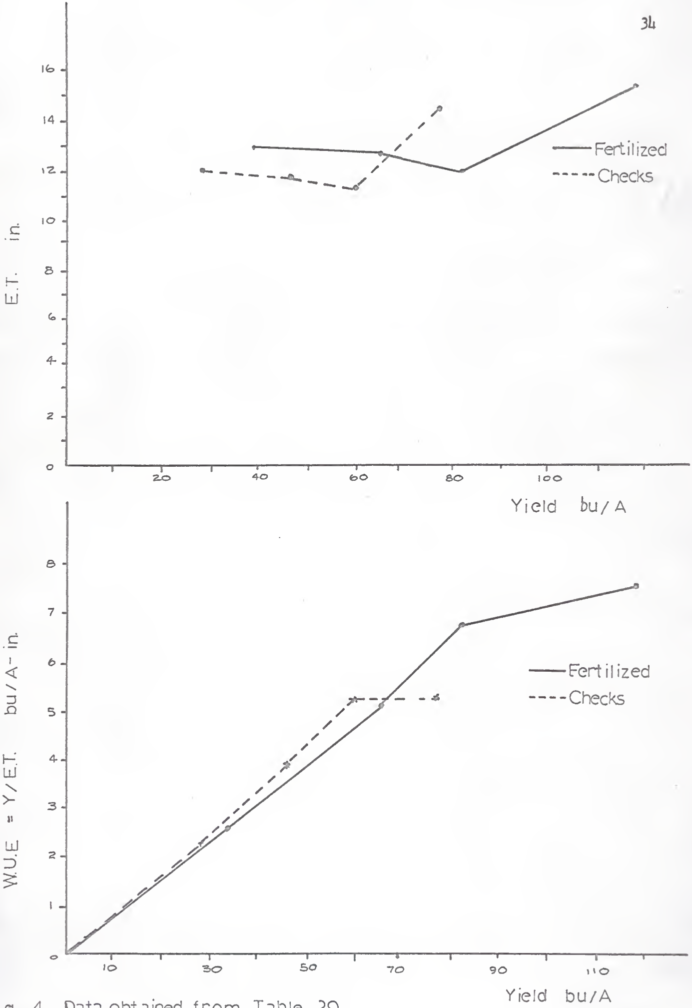

Fig. 4 Data obtained from Table 29

a complete cover is obtained. This fact was observed by Penman (19) in England with orchardgrass. Also Schofield at Rothamsted (22) confirmed this fact using lysimters measurements.

Some experiments reported before fit also into this pattern, for example, the work of Carlson et al (3) shown in figures 5 and 6 and the Musick experiment in figure 7.

Model E states that the evapotranspiration decreases as yield increases. No experiments reported fit this model.

Model F corresponds to a case when evapotranspiration increases faster than yield increases. It is also not a common situation.

Considering case (II) of Black's interpretation, when moisture supply is not abundant, conclusions are entirely different. In arid and semi-arid conditions the available water has been exhausted to the full depth of wetting by the time the crop is mature. Hence the exhaustion pattern of water supply under these conditions is conducive to a depression of grain yield when fertility level is raised. The reason for this is that the relative good supply of water early in the crop season (early precipitations, long fallow period) permits a luxuriant growth if fertility is high. This will cause the water supply to be depleted more rapidly than if fertility is moderate or low. Therefore, one of the problems of dryland agriculture is to determine whether there are favorable moisture interludes in the cycle of plant development when the soil cannot supply sufficient nutrients for maximum growth. If, in these periods, fertilizers can increase the rate of growth without exhausting water at a faster rate, then total yield and water use efficiency can be increased. If fertilizers accelerate the rates of both growth and water use, the yield and water use efficiency will depend on the total supply of water and the status of the crop when the moisture supply

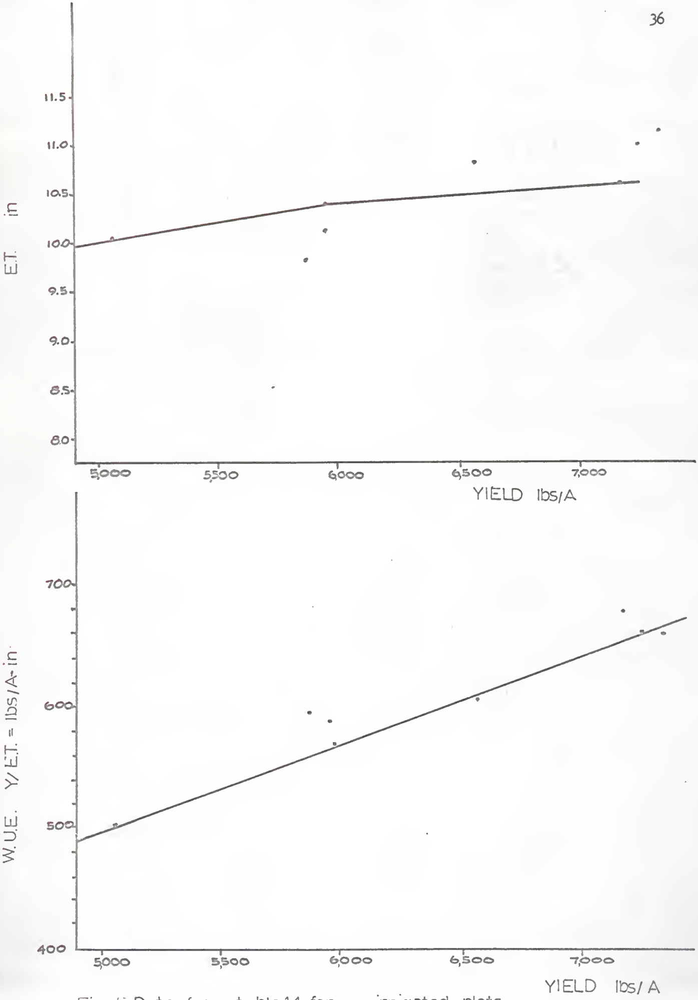

Fig. 5 Data from table 14 for non-irrigated plots

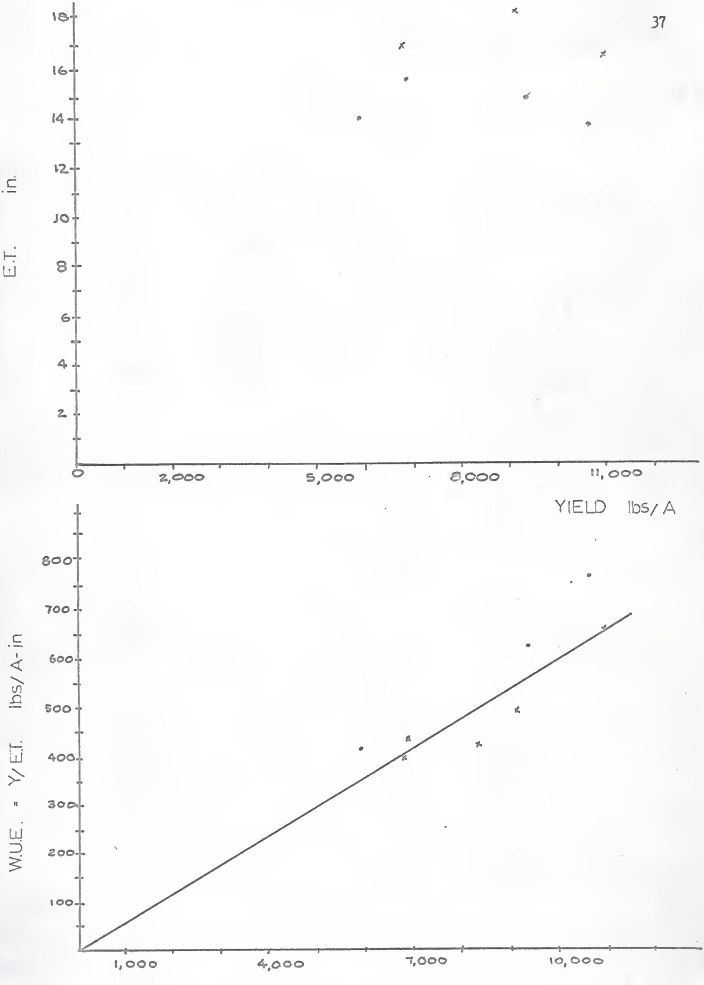

Fig 6 Data from table 14 for irrigated plots

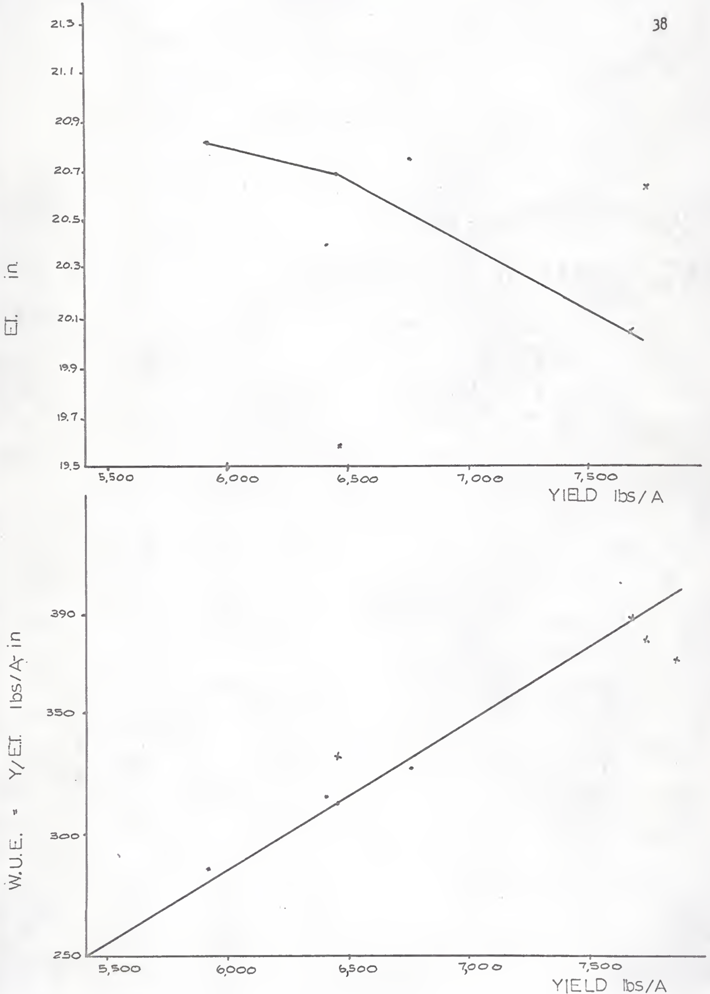

Fig 7 Data obtained from table 27

becomes exhausted. Thus, accelerated water use through fertilization can be disastrous for grain crops if the soil moisture supply is exhausted and rains do not come before the grain is filled.

In several experiments reported here, the crops had developed in moisture shortage conditions. For example, in the Carlson experiment (3) shown in figure 5; on dryland, nitrogen fertilization did not affect yields, water use or water use efficiency significantly in either year. Forage produced per acre inch of water was higher without irrigation than with irrigation unless a high nitrogen rate and thick stand were used together. Hence, water use efficiency is frequently greater on dryland than on irrigated land. Also, in Jensen's and Sletten's work (Table 20) water was certainly a limiting factor on the M_1 treatment, where the crop had had only preplanting irrigation.

SUMMARY

References on the relationships of soil moisture and response to application of nitrogenous fertilizers on small grains and row crops were collected and arranged according to date of publication. In cases where information was available, the water use efficiency coefficient was calculated according to Viets' directions to compare the effect of nitrogen fertilization on water economy. It was demonstrated that when soil moisture was sufficient to meet a crop's need, the use of nitrogenous fertilizers increased water use efficiency if the soil was deficient in this nutrient at the time of application. When moisture content was not sufficient the water use coefficient did not change noticeably. Several patterns of relations between evapotranspiration vs. yield, and water use efficiency vs. yield proposed by Viets were applied to the different experiments to obtain a better understanding of nitrogen fertilizer action upon water use.

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RELATIONSHIPS BETWEEN NITROGEN FERTILIZATION, SOIL MOISTURE, AND YIELD OF CROPS

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The purpose of this report, was to collect and discuss information obtained in the United States and abroad concerning the influence of the relationships between nitrogenous fertilizer use and soil moisture on the yields of small grains and row crops.

The information found was not abundant, mostly due to the fact that it was usually very expensive and laborious to maintain the moisture content at a constant level in the field when a large number of plots were included in the experiments. Most information collected was obtained from irrigated areas, where water must be used efficiently in order to maximize profits.

This literature review was divided into two definite periods named "early" and "modern" experiments. Most "early" experiments were conducted using pot containers, under greenhouse conditions; the "modern" experiments were generally conducted in experimental fields.

Early workers, dating back to 1850, pointed out that fertilizers in general, and especially nitrogen, reduced water requirements of common crops. However, most of these experiments were set up to determine only the water requirement which was a useless value compared with the evapotranspiration value measured in modern experiments.

Several authors have used very different approaches to explain the nitrogen-moisture relationship. The best experiments included several doses of nitrogen fertilizers following a uniform application of other nutrients, such as phosphorus and potassium. Irrigation treatments were superimposed, including at least two moisture levels. Yield and evapotranspiration records were taken for each plot. In cases where there was enough available water during the crop season to meet the water requirements of plants, evapotranspiration, in general, increased with nitrogen fertilization, but if the soil was nitrogen deficient to a certain extent, production increase was higher than evapotranspiration increase, and hence water was used more efficiently. The Viets' concept of water-use efficiency was applied by the author to some of the best designed experiments. This ratio, and the evapotranspiration value, were plotted against the yield values obtained. Two definite patterns of curves were obtained, rather than the six which are possible, according to Viets' interpretations. When water supply was not sufficient to meet crop needs variable results were obtained. In some cases, the water-use efficiency coefficient was increased, but to a small extent.

In general, it was considered unsafe to advise indiscriminate use of nitrogenous fertilizer under dryland conditions due to unpredictable drought periods, but on the other hand, it was also concluded that rational nitrogen fertilizations, on nitrogen deficient soils, increased grain yields without a correlative increase in water use.