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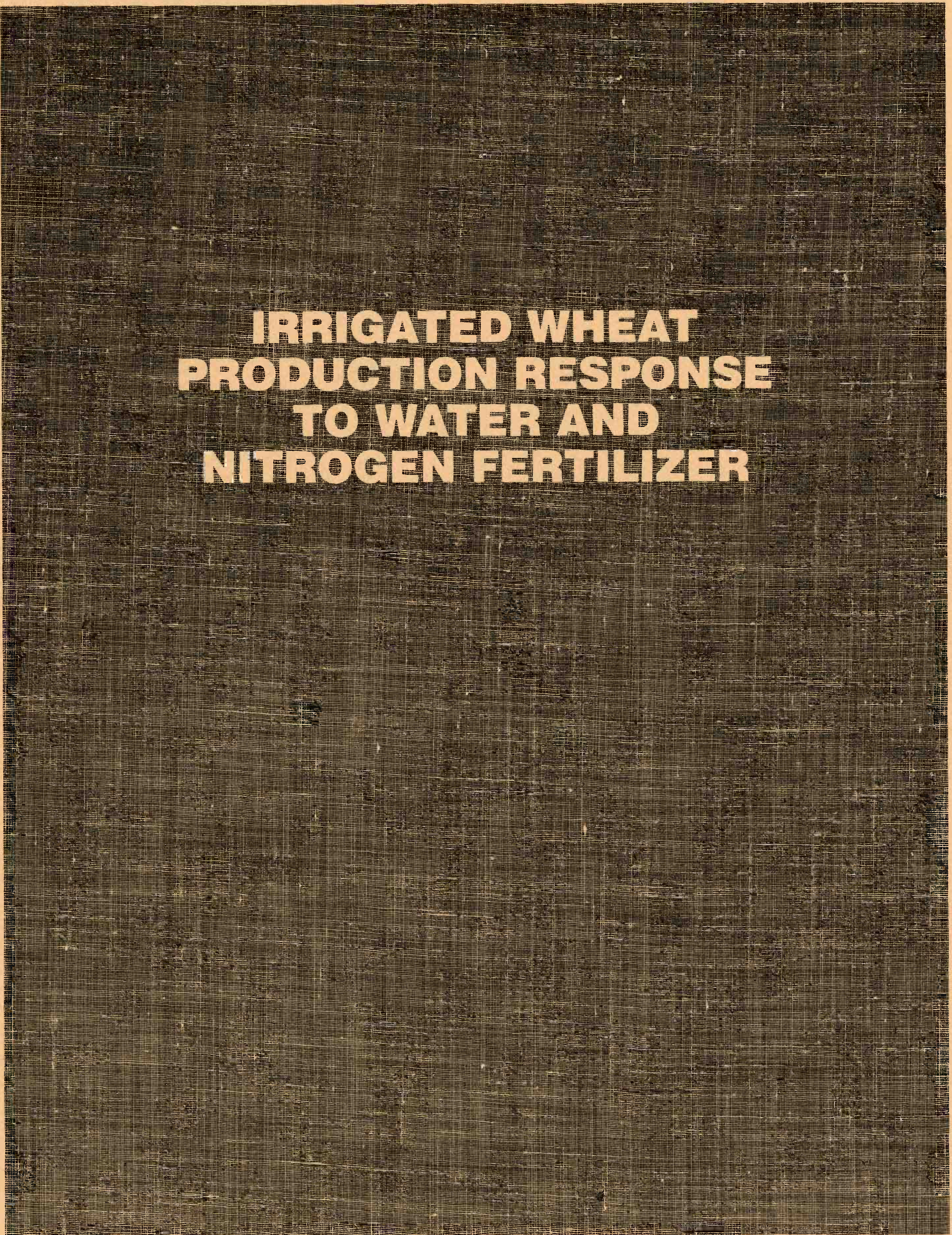

IRRIGATED WHEAT PRODUCTION RESPONSE TO WATER AND NITROGEN FERTILIZER

Agricultural Experiment Station
The University of Arizona

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CONTENTS

FIGURES

TABLES

Table No. Page

INTRODUCTION

Wheat is highly adapted to Arizona's irrigated agriculture and fits well in most crop rotations. It is grown during the winter and spring months when rates of evapotranspiration are low and the water use of most other crops is at a minimum. Stiff-strawed, semi-dwarf spring wheats have been responsible for production increases from 23,000 acres in 1966 to over 300,000 acres in 1975. Most of the latest increases result from a demand for export milling wheat. Traditionally, wheat has been utilized as a human food. Recent developments in the livestock feeding industry have demonstrated its value as a feed grain and its use as a livestock feed has increased significantly. The rapid growth of cattle feeding in Arizona has increased demand for all feed grains, including wheat.

Principal cultural factors limiting wheat production in Arizona are nitrogen fertilizer and water. Soils are low in organic matter and residual nitrogen. Rainfall is sparse and irrigation water is usually limited and/or expensive. Nitrogen-water-yield relationships must be defined for short-stature wheats in order to identify optimum economic use of fertilizer and water inputs. Focus on the net value return for each unit of water or nitrogen used for wheat production is an inevitable result of the energy and fuel crisis; resulting in increased costs of nitrogen, and ultimately higher costs of irrigation water.

OBJECTIVES

This study is a part of a project contracted by Iowa State University and the University of Arizona with the Bureau of Reclamation, U.S. Department of Interior to provide information for agronomic and economic evaluation of irrigation developments (4). The main objectives of the experiments reported here were to determine semi-dwarf spring wheat yield and quality response to varying inputs of irrigation water and nitrogen fertilizer for various soil environments. Estimates of response functions of water and nitrogen in relation to yield and grain quality, and plant and soil characteristics are useful in production planning for optimum utilization of available resources at farmer, and regional levels.

Determining the most valuable use levels of water and nitrogen is a contribution to farmer decision making in allocation of resources for producing wheat or alternate crops. On a wider and more comprehensive basis, decisions regarding allocation of inputs, both to interregional (irrigation districts) and regions may be guided. Studies such as these generate the data necessary to determine the value of water and nitrogen associated with different conditions. Irrigation development projects can develop and allocate water for areas in which the estimated value productivity is greatest. The reallocation of water from agriculture to urban use is a critical problem in some areas of the western United States. Decisions upon which such action is justified or rejected, and on pricing policies to regulate it can be developed from estimates of agricultural input in relation to yield, demand, and price.

REVIEW OF RELATED LITERATURE

There are numerous publications concerning nitrogen and water relationships to wheat production and quality. Most have been with wheat types and cultural conditions generally different from those in Arizona (5, 6, 8, 9, 10, 11, 12, 13). Viets (14), in a 1962 review, reported a common observation of enhanced water use efficiency due to fertilizer if the treatment increased yields. He concluded that adequate nutrition was a factor of major importance in the efficient use and conservation of water resources. In Nebraska (11), water use efficiency of winter wheat was increased an average of 12% by optimum fertilizer treatment. This increased efficiency was especially associated with yield increase and accompanied by an extra inch of consumptive water use. In cases of large fertilizer responses, water use efficiency was increased more than 100%.

Mexican researchers, Fernandez and Laird (3) reported on a 1-year nitrogen x irrigation study in 1956. They grew the variety Yaqui 54 in a salty, clay soil. Grain yields were increaesd 85% with adequate moisture. Maintenance of available soil moisture above 30% was necessary for maximum grain yields. The protein content of the grain was decreased by small applications of nitrogen and increased by large applications. Protein content was lowest in the wettest treatment and highest in the driest treatment.

McNeal (8) grew five spring wheat genotypes under dryland farming conditions in Montana, but with adequate soil moisture. There was no nitrogen x genotype interaction for yield between short, medium and tall genotypes. Water use increased significantly with increased rates of nitrogen and tall or medium height cultivars showed the greatest water use efficiency.

Semi-dwarf spring wheat variety performance at the California Imperial Valley Field Station, where conditions are similar to those in Southern Arizona, was summarized by Lehman and Qualset (7). No yield difference was shown between applications of 120 and 240 pounds N per acre. They stressed the importance of adequate soil moisture through the growing season and through maturity. Day and Intalap (1) concluded that the jointing stage was the critical stage for moisture in the production of the semi-dwarf variety, Maricopa. However, soil moisture stress at any stage of growth decreased yield.

The increased planting of semi-dwarf wheat at early dates caused Erie (2) to revise his estimates of consumptive water use for wheat in Central Arizona. In a two-year study at the University of Arizona's Mesa Experiment Farm, he found high yielding semi-dwarf wheats had a consumptive use of 25.8 inches of water, which represented an increase of at least 3.0 inches over varieties grown previously.

MATERIALS AND METHODS

Semi-dwarf spring wheat was grown at three locations, the University of Arizona Mesa, Yuma Valley, and Yuma Mesa Experiment farms for two years, 1971 and 1972. Each test consisted of two or three blocks of a 5 × 5 incomplete factorial design. Each block consisted of 22 plots with unequal replication of thirteen treatment combinations of five irrigation and five nitrogen levels (Figure 1).

FIGURE 1

Number of plots in each block for each of five nitrogen and five irrigation treatments in incomplete factorial experimental design with 22 plots and 13 treatment combinations.

Nitrogen treatments						
	N_1	2	0	2	0	2
	N_2	0	1	0	1	0
	N_3	2	0	2	0	2
	N_4	0	1	0	1	0
	N_5	2	0	2	0	2
		I_1	I_2	I_3	I_4	I_5

Irrigation treatments

MESA

The Mesa site was a Laveen clay loam soil which had been in alfalfa production in the spring of 1970. The average bulk density of 16 samples encompassing 18 inches of soil depth was 1.4 grams per cubic centimeter. Several soil samples were composited into single samples for 0-1, 1-2, and 2-3 foot depths. Average field capacity was 17.6%, wilting point 8.1% and available water holding capacity 1.6 inches per foot. The land was chiseled 20 inches deep in two directions to break up compaction layers from previous haying operations. A crop of sorghum was grown during the summer without fertilization to remove available nitrogen. After the sorghum top growth was removed in October, 250 pounds of treble superphosphate per acre were applied. The seedbed was prepared and irrigated with eight inches of water to fill the soil profile to field capacity. Siete Cerros, a feed wheat, was drilled into moisture at a seeding rate of 55 pounds per acre, November 15, 1970. Previously designated plots of 400 square feet each were bordered up for basin-type irrigation.

Nitrogen fertilizer levels selected for this test were 0 (N_1), 75 (N_2), 150 (N_3), 225 (N_4) and 300 (N_5) pounds of N per acre. Prilled ammonium nitrate was applied in three equal applications. The first was worked into the seedbed prior to planting, the second was applied near jointing stage and the third during boot stage of plant development. The second and third nitrogen application for the very dry moisture levels coincided with the two post-emergence irrigations.

Prior to each irrigation, two or three soil samples were taken at 0-1, 1-2, and 2-3 foot depths. Soil moisture percentages were determined gravimetrically and irrigations were made when the percentage of available soil moisture used in the top three feet averaged 42 (I_5), 60 (I_4), 70 (I_3), 82 (I_2) and 95 (I_1). "Irrometer"* tensiometers were used as a guide to indicate when soil samples should be taken, thus excessive sampling was avoided. Soil moisture percentages, percent of available soil moisture used, and soil moisture tensions, as determined in the laboratory, are presented in Table 1.

TABLE 1

Average soil moisture percent, percent of available soil moisture used and soil moisture tension before irrigating for five soil moisture levels. Laveen clay loam, Mesa, 1971 and 1972.

Soil Moisture level	Soil Moisture %	Available Moisture % Used	Soil Moisture tension in atmospheres
I_1 Very dry	8.5	95	12.0
I_2 Dry	9.8	82	5.0
I_3 Medium	11.0	70	2.0
I_4 Wet	12.0	60	1.0
I_5 Very wet	13.6	42	.7

The second experiment was adjacent to the first on land with the same soil, moisture and cropping history. Barley was grown in the 1970–71 season. The same procedure of phosphate fertilization, land preparation, preplant irrigation, nitrogen fertilizer application and planting was followed as in the first experiment. Seeding date was November 19, 1971.

Nitrogen fertilizer applications for this test were 0 (N_1), 80 (N_2), 160 (N_3), 240 (N_4) and 320 (N_5) pounds of N per acre. From soil test analyses for NO_3-N, an estimate of 125 pounds of residual N per acre was calculated for a depth of four feet. Consequently, the data analysis was handled on the basis of 125, 205, 285, 365 and 445 pound nitrogen levels.

Irrigation levels and procedure, data collection and other aspects of the two tests were alike. Rainfall during the production period of both years was minimal and not a significant production factor. Very little moisture from rain reached the root zone. Individual irrigations for both tests varied from 4.0 inches for the very wet plots to 5.8 inches for the very dry plots. Only the medium treatment level was calculated to actually replace moisture used. Flood irrigations of four inches or more were made for uniform water penetration. Water did not stand on the plots. The excess water applied to the very wet plots can be accounted for by deep percolation. Conversely, 5.8 inches applied to the very dry plots did not replace all the water used to six feet. At the Mesa Farm, wheat uses water to a depth of six feet or more. Approximately 13% of the average consumptive water use of wheat comes from below three feet (2).

Wheat production data were obtained from 48 square feet in the center of each plot. Plots were cut with a hand sickle and threshed with a Vogel plot thresher. Samples of the grain from all plots were analyzed by the Kjeldahl Method for total nitrogen and converted to total protein by the factor 5.7.

YUMA VALLEY

The Glenbar silt loam top soil of the Yuma Valley Farm is fairly uniform to a minimum depth of approximately 30 inches, and is underlain with various subsoil layers ranging from clay to washed sand. Field capacity of the 1971 experimental site was 30.0%, the permanent wilting point was 14.0% and average available water holding capacity was 2.8 inches per foot. The land received 225 pounds of treble superphosphate

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*Descriptive trade name, no product endorsement intended.

per acre during seedbed preparation. Inia 66, a milling wheat, was drilled at 75 pounds per acre, and a germination irrigation of 9.6 inches was applied December 11, 1970. This supplied enough water to bring the soil to field capacity to a depth of four feet. Plots of 400 square feet were formed into irrigation basins. Soil moisture levels were determined gravimetrically to a depth of three feet. Irrigations were applied when the available soil moisture in the second foot was 45 (I_5), 55 (I_4), 65 (I_3), 75 (I_2) and 85 (I_1) percent used. Sufficient water to replace that actually used to a depth of three feet was applied in each irrigation. Relation of soil moisture percent to available soil moisture used is presented in Table 2. The nitrogen fertilizer for the 75 (N_2) and 150 (N_3) pounds per acre treatments were applied before planting. The 225 (N_4) and 300 (N_5) pound rates were split equally between two applications, preplant and the preboot plant growth stages.

TABLE 2

Average soil moisture percent and percent of available soil moisture used before irrigating for five soil moisture levels. Glenbar silty clay loam, Yuma Valley, 1971.

Soil Moisture Level	Soil Moisture %	Available Soil Moisture % Used
I_1 Very dry	16.4	85
I_2 Dry	18.0	75
I_3 Medium	19.6	65
I_4 Wet	21.2	55
I_5 Very wet	22.8	45

The 1972 experiment was on a similar Glenbar silty clay loam soil, but at a different site. Field capacity was variable but averaged 34.0% in the second foot, the permanent wilting point was 14.8% and the available water holding capacity was 3.3 inches per foot. Irrigation treatments were based on percent of available water used in the second foot as presented in Table 3. Soil test analyses indicated an average of 50 pounds residual N for a depth of three feet. In addition, the nitrogen applications were 0 (N_1), 50 (N_2), 100 (N_3), 150 (N_4) and 200 (N_5) pounds per acre. Method of nitrogen application, irrigation procedure and levels, and other aspects of the two tests were alike. Rainfall during the production periods for both years was minimal and not a significant production factor. Irrigation quantities for each irrigation varied from 3.8 to 9.1 inches as calculated to replace water used.

TABLE 3

Average soil moisture percent and percent of available soil moisture used before irrigating for five soil moisture levels. Glenbar silty clay loam, Yuma Valley, 1972.

Soil Moisture Level	Soil Moisture %	Available Soil Moisture % Used
I_1 Very dry	17.7	85
I_2 Dry	19.6	75
I_3 Medium	21.5	65
I_4 Wet	23.4	55
I_5 Very wet	25.4	45

Wheat production data were obtained by harvesting 200 square feet from the center of each plot with a plot combine. Samples of the grain from all plots were analyzed by the Kjeldahl Method for total nitrogen content and converted to crude protein by the factor 5.7.

YUMA MESA

The Superstitution fine sand of the Yuma Mesa has very little stratification. The 1971 experimental area had a profile of continuous fine sands with occasional pebbles and lime accretions to a depth of six feet. The water intake rate was approximately 2.9 inches per hour. Field capacity (1/10 atmospheres) was 7.30%, permanent wilting point was 4.16%, and available water holding capacity averaged 0.6 inches per foot. The land received 200 pounds P_2O_5 and 25 pounds N per acre during seedbed preparation. Inia 66 was drilled at 100 pounds per acre. Beginning with the germination irrigation December 9, 1970, five uniform irrigations were applied to establish the stand. After the plots were formed into irrigation basins of 400 square feet, they were uniformly irrigated with 2.4 inches of water February 4. Succeeding irrigations were made when the available soil moisture in the second foot was 45 (I_1), 55 (I_2), 65 (I_3), 75 (I_4) and 85 (I_5) percent used. The relation of soil moisture percent to available soil moisture used is presented in Table 4. Frequent irrigations ranging from 1.6 to 2.4 inches were required to replace water used. Nitrogen was applied with each irrigation in increments of 20 to 100 pounds N per acre, depending upon the number of irrigations necessary to meet the specified water requirements. Total fertilization in pounds of N per acre was as follows: 25 (N_1), 100 (N_2), 175 (N_3), 200 (N_4) and 325 (N_5).

TABLE 4

Average soil moisture percent, percent of available soil moisture used and soil moisture tension before irrigating for five soil moisture levels. Superstitution fine sand, Yuma Mesa, 1971.

Soil Moisture Level	Soil Moisture %	Available Moisture % Used	Soil Moisture Tension in Atmospheres
I_1 Very dry	4.5	85	2.40
I_2 Dry	5.1	75	1.30
I_3 Medium	5.6	65	0.83
I_4 Wet	6.2	55	0.55
I_5 Very wet	6.7	45	0.33

The 1972 experiment was planted December 13, 1971, and lightly irrigated for stand establishment December 15 and 20. The experimental site had a field capacity of 7.8% in the second foot, a permanent wilting point of 4.2% and the available water holding capacity was 0.7 inches per foot. Irrigation treatments were based on soil moisture percent as related to percent of available water used and are presented in Table 5. Twenty-five pounds of N per acre were applied dur-

TABLE 5

Average soil moisture percent, percent of available soil moisture used and soil moisture tension before irrigating for five moisture levels. Superstitution fine sand, Yuma Mesa, 1972.

Soil Moisture Level	Soil Moisture %	Available Moisture % Used	Soil Moisture Tension in Atmospheres
I_1 Very dry	4.5	85	2.4
I_2 Dry	5.2	75	1.2
I_3 Medium	5.8	65	0.8
I_4 Wet	6.5	55	0.4
I_5 Very wet	7.1	45	0.2

additional N applied as follows: 38 (N_1), 138 (N_2), 188 (N_3), 238 (N_4) and 288 (N_5) pounds per acre. All other aspects of irrigation, fertilization and data collection were the same as in the 1971 experiment.

ing seedbed preparation for stand establishment. After stand establishment, soil analyses showed 38 pounds of residual N per acre in three feet. Consequently, data analysis was handled on the basis of residual N plus

RESULTS AND DISCUSSION

The field experiments provided input-output data at specific locations. This data is directly applicable to studies of resource efficiency and economic returns for the soil types on which the experiments were conducted. The variability of soil characteristics among the individual experiments (Appendix Tables A-19 to A-21) provides an insight into the role of soil features in plant-water-fertilizer relationships. Year-to-year and location-to-location fluctuations in nitrogen or water input generally prohibited combining the data in the analyses. Treatment combinations, grain yield, grain quality and growth responses for the six experiments described in Materials and Methods are presented in Tables 6 to 11, respectively. As the experiments were specifically designed for fitting a curvilinear response surface such as the second-order polynomial (quadratic) function no attempt was made to define significant differences between treatment means. This functional form was chosen because of its general suitability to plant-soil-water relationships.

TABLE 6

Treatment combinations and corresponding average grain yield, test weight, percent protein, plant height, days to flower and percent lodged at maturity for Siete Cerros semi-dwarf wheat grown in Laveen clay loam soil, Mesa, Arizona, 1971.

	Treatments			Incomplete Factorial Averages (2 blocks)					
	Water[1] Used (inches)	Soil Moisture (% used)	Nitrogen[2] Applied (lbs/acre)	Yield (lbs/acre)	Test Weight (lbs/bu)	Total Protein (%)	Plant Height (inches)	Time to Flower (days)	Lodged (%)
I_1N_1	16.3	95	0	2686	63.2	8.1	27.8	132	0
I_3N_1	23.9	70	0	2815	62.9	8.0	28.5	133	0
I_5N_1	23.5	42	0	2783	62.6	7.8	28.3	133	0
I_2N_2	21.8	82	75	5724	64.1	10.6	31.5	134	0
I_4N_2	29.7	60	75	6641	63.5	10.0	32.5	136	0
I_1N_3	17.9	95	150	5424	63.3	10.7	29.3	134	0
I_3N_3	29.1	70	150	7387	63.1	11.4	34.5	137	0
I_5N_3	33.7	42	150	6817	61.8	10.6	35.8	139	38
I_2N_4	27.5	82	225	7259	62.3	11.6	33.0	136	0
I_4N_4	33.8	60	225	7349	62.8	10.8	35.5	138	15
I_1N_5	23.3	95	300	6237	63.4	12.2	32.3	134	0
I_3N_5	30.5	70	300	7179	62.6	11.2	35.0	140	0
I_5N_5	33.7	42	300	6231	60.6	11.1	36.8	142	56

[1] Excludes residual soil moisture as calculated to a depth of four feet at grain maturity. Soil moisture was virtually exhausted to four feet except for 1.6" for I_1, N_1, 2.8" for I_3 N_1, and 1.2" for I_5N_1.

[2] Does not include minimal residual N from previous crop.

TABLE 7

Treatment combinations and corresponding average grain yields, test weight, percent protein, plant heights, days to flower and percent lodged at maturity for Siete Cerros semi-dwarf wheat grown in Laveen clay loam soil, Mesa, Arizona, 1972.

	Treatments			Incomplete Factorial Averages (2 blocks)					
	Water[1] Used (inches)	Soil Moisture (% used)	Soil[2] Nitrogen (lbs/acre)	Yield (lbs/acre)	Test Weight (lbs/bu)	Total Protein (%)	Plant Height (inches)	Time to Flower (days)	Lodged (%)
I_1N_1	17.6	95	125	5434	63.5	11.8	33.8	123	0
I_3N_1	28.5	70	125	6443	64.0	11.0	36.3	128	0
I_5N_1	29.0	42	125	6486	63.5	10.7	39.0	130	5
I_2N_2	21.2	82	205	6203	63.3	12.1	36.0	126	0
I_4N_2	29.9	60	205	6793	63.5	11.7	37.5	131	0
I_1N_3	22.6	95	285	5878	63.8	12.5	34.5	125	0
I_3N_3	33.9	70	285	6734	63.0	12.6	37.8	129	0
I_5N_3	37.1	42	285	4942	61.8	12.7	39.3	137	95
I_2N_4	26.5	82	365	7033	63.0	12.0	36.0	127	0
I_4N_4	30.8	60	365	6185	63.3	12.1	39.0	134	60
I_1N_5	23.0	95	445	5915	63.9	12.9	34.8	126	0
I_3N_5	33.5	70	445	6382	63.1	12.4	39.8	132	35
I_5N_5	36.5	42	445	5155	61.8	12.4	40.5	138	100

[1] Excludes residual soil moisture as calculated to a depth of four feet at grain maturity. Soil moisture was virtually exhausted to four feet. Exceptions were 1.0" and 0.9" for I_2N_2 and I_2N_4, 1.5" and 1.9" for I_3N_1 and I_3N_5, 2.9" and 1.4" for I_4N_2 and I_4N_4, and 1.6", 1.3" and 1.9" for I_5N_1, I_5N_3 and I_5N_5, respectively.

[2] Includes 125 lbs residual N calculated to a depth of four feet.

TABLE 8

Treatment combinations and corresponding average grain yields, test weight and percent protein for Inia 66 semi-dwarf wheat grown in Glenbar silty clay loam soil, Yuma Valley, Arizona, 1971.

	Treatments			Incomplete Factorial Averages (2 blocks)		
	Water[1] Applied (inches)	Soil Moisture (% used)	Nitrogen[2] Applied (lbs/acre)	Yield (lbs/acre)	Test Weight (lbs/bu)	Total Protein (%)
I_1N_1	27.2	85	0	2957	64.3	10.6
I_3N_1	33.1	65	0	3398	64.2	8.8
I_5N_1	46.9	45	0	4655	63.9	8.7
I_2N_2	31.7	75	75	4901	64.5	9.3
I_4N_2	37.5	55	75	5151	64.8	13.4
I_1N_3	27.2	85	150	3899	64.3	13.2
I_3N_3	33.1	65	150	3773	64.3	13.5
I_5N_3	47.4	45	150	6077	64.1	12.8
I_2N_4	32.7	75	225	4280	64.3	14.1
I_4N_4	39.9	55	225	6164	64.3	13.5
I_1N_5	27.2	85	300	3632	64.1	14.9
I_3N_5	33.1	65	300	4792	64.0	14.3
I_5N_5	47.5	45	300	6213	64.4	14.3

[1] Includes excess residual water from the last irrigation, estimated as 4.6" for I_1, 7.0" for I_2, I_3 and I_4, 9.0" for I_5.

[2] Does not include residual N from the previous crop.

TABLE 9

Treatment combinations and corresponding average grain yields, test weight, percent protein and plant heights for Inia 66 semi-dwarf wheat grown in Glenbar silty clay loam soil, Yuma Valley, Arizona 1972.

	Treatments			Incomplete Factorial Averages (3 blocks)			
	Water[1] Used (inches)	Soil Moisture (% used)	Nitrogen[2] Used (lbs/acre)	Yield (lbs/acre)	Test Weight (lbs/bu)	Total Protein (%)	Plant Height (inches)
I_1N_1	17.9	85	50	3045	64.8	12.9	28.8
I_3N_1	21.9	65	50	3638	64.8	12.0	32.5
I_5N_1	24.0	45	50	3888	64.7	12.4	32.2
I_2N_2	22.2	75	100	4219	65.2	12.6	32.0
I_4N_2	26.5	55	100	4800	63.3	12.6	33.0
I_1N_3	19.7	85	150	3065	64.6	14.8	28.8
I_3N_3	25.4	65	150	4606	64.8	13.5	34.2
I_5N_3	26.4	45	150	5227	65.3	12.6	31.8
I_2N_4	23.6	75	200	4114	65.0	14.6	32.0
I_4N_4	27.5	55	200	5348	64.8	13.3	32.7
I_1N_5	19.4	85	250	3432	64.8	15.0	29.8
I_3N_5	28.6	65	250	4993	64.8	15.0	33.0
I_5N_5	27.5	45	250	5239	65.2	14.0	32.5

[1] Excludes calculated residual soil moisture to a depth of three feet at grain maturity, ranging from 1.0" for I_3N_3 to 5.7" for I_2N_2.

[2] Includes residual N calculated to a depth of three feet.

TABLE 10

Treatment combinations and corresponding average grain yield, test weight and percent protein for Inia 66 semi-dwarf wheat grown in Superstitution fine sand, Yuma Mesa, Arizona, 1971.

	Treatments			Incomplete Factorial Averages (2 blocks)		
	Water[1] Used (inches)	Soil Moisture (% used)	Nitrogen[2] Applied (lbs/acre)	Yield (lbs/acre)	Test Weight (lbs/bu)	Total Protein (%)
I_1N_1	22.4	85	25	568	62.1	8.1
I_3N_1	27.6	65	25	521	62.9	9.7
I_5N_1	41.0	45	25	519	62.9	8.9
I_2N_2	25.6	75	100	1176	64.0	13.0
I_4N_2	34.0	55	100	2276	63.2	10.8
I_1N_3	22.8	85	175	1151	63.6	15.4
I_3N_3	28.4	65	175	1829	63.9	17.2
I_5N_3	41.6	45	175	3147	63.7	8.6
I_2N_4	26.0	75	250	1818	63.5	15.2
I_4N_4	35.2	55	250	3653	64.0	11.7
I_1N_5	23.2	85	325	1614	62.7	16.0
I_3N_5	28.8	65	325	2181	63.1	13.2
I_5N_5	42.4	45	325	3988	63.9	13.6

[1] Does not include available water remaining in the root zone when the wheat was mature.

[2] Does not include residual N carry-over from previous crop, estimated near 0.

TABLE 11

Treatment combinations and corresponding average grain yield, test weight, percent protein and plant height for Inia 66 semi-dwarf wheat grown in Superstitution fine sand, Yuma Mesa, Arizona, 1972.

	Treatments			Incomplete Factorial Averages (3 blocks)			
	Water[1] Used (inches)	Soil Moisture (% used)	Soil[2] Nitrogen (lbs/acre)	Yield (lbs/acre)	Test Weight (lbs/bu)	Total Protein (%)	Plant Height (inches)
I_1N_1	12.0	85	38	750	64.2	9.8	17.0
I_3N_1	13.2	65	38	1016	64.0	8.6	20.5
I_5N_1	22.8	45	38	1388	62.8	8.2	21.5
I_2N_2	19.2	75	138	1468	64.5	14.3	22.8
I_4N_2	23.2	55	138	3468	65.0	12.2	25.8
I_1N_3	14.4	85	188	1798	64.4	14.8	19.5
I_3N_3	20.0	65	188	3219	64.6	14.1	25.3
I_5N_3	27.2	45	188	4461	65.1	12.3	27.8
I_2N_4	20.8	75	238	2856	64.6	14.8	24.7
I_4N_4	22.0	55	238	3130	65.0	14.4	25.3
I_1N_5	15.6	85	288	1573	64.4	15.9	20.3
I_3N_5	18.0	65	288	1907	64.2	16.0	24.3
I_5N_5	30.8	45	288	5292	64.9	12.5	29.3

[1] Does nou include available water remaining in the root zone when the wheat was mature.

[2] Includes residual N from previous crop calculated to three foot depth.

Estimated production functions were derived by multiple regression analysis of the data collected. Production function analysis techniques utilized for examining input-output relationships have been described by Hexem and Heady (4). They fitted several functional forms to each set of experimental data presented in their bulletin and selected the quadratic, square root, and three-halves functions as the best suited. The criteria for selection of the best functions included the value of R^2, the F value for the function, statistical significance of the estimated coefficients and the signs of the coefficients. These factors were generally similar for all three functions.

The curvilinear response surfaces of the quadratic production function were selected as appropriate to the analysis of these experiments. The model is presented in the following equation.

$$Y = a + b_1I + b_2N + b_3I^2 + b_4N^2 + b_5IN$$

where:
Y = yield of wheat grain in pounds per acre,
a = intercept value,
b_1 = regression coefficients,
I = percent of available soil moisture depletion when irrigated, and
N = amount of fertilizer applied or available in pounds nitrogen per acre.

The I^2 and N^2 terms permit the response surface to curve downward at the point of optimum input estimates and to show negative marginal physical products. Marginal products can be described as the measure of the increment of yield attributable to one unit increment of input.

With a knowledge of expected response, efficient use of water and nitrogen resources can be made. Maximum yield estimates are calculated from marginal physical product equations. Economists can use production response functions to define those input levels and combinations that will maximize producer profit when evaluating wheat response from available resources for soils with similar characteristics and environment. Quadratic production functions for wheat grain yields are found in Table 12 for each year, location and soil type in these experiments.

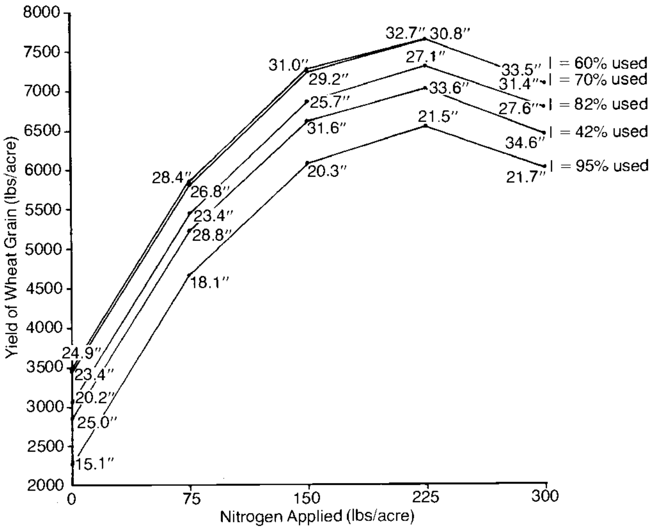
MESA

The high R^2 value for Equation 1 (Mesa, 1971), which explains 93% of the variation in grain yield, the highly significant F-ratio for the overall regression, and the high significance of the I, N, I^2 and N^2 regression coefficients portray this production function as a very useful instrument for predicting yield from prescribed irrigation and nitrogen inputs. Although the F-ratio and the regression coefficients are significant, with R^2 explaining 58% of the yield variation, Equation 2 (Mesa, 1972) is not as useful for response predictions because of a lower degree of "goodness of fit" and lack of curvilinearity in the response surface. This results from the absence of low nitrogen input treatments in the experiment (Table 7).

The function for Mesa, 1971, was used to predict grain yields expected from varying applications of irrigation water and nitrogen. Predictions are presented in table form (Appendix Table A-1). The individual input response curves for different percent water used values are plotted in Figure 2. They reveal the nature of the response of wheat grain yield to nitrogen as irrigation is held constant at five alternative levels of soil moisture use. Predicted amounts of water necessary to secure this response are plotted from the production function and predicted values in Appendix Table A-3. They are specific to the irrigation delivery efficiency and methods of the 1971 Mesa Experiment.

FIGURE 2

Wheat grain production as related to varying soil nitrogen levels and soil moisture use, Mesa, 1971.[1]



[1] Figures on curves indicate inches of water required for specified nitrogen and soil moisture levels.

Source: Appendix Tables A-1 and A-3.

With the irrigation water delivery and growing conditions similar to those of this experiment, maximum grain yield (7600 lbs/acre) can be expected by scheduling irrigations when 60 to 70% of soil moisture is de-

TABLE 12

Quadratic production functions for wheat grain yields at three locations and soil types and two years of variable input of irrigation levels and nitrogen.

	R^2	F
(1) Mesa, Laveen clay loam—1971.		
(.000)[1] (.000) (.000) (.000) (.718)		
$Y = -1662.94270 + 160.11296\ I - 1.25212\ I^2 + 37.61638\ N - .08739\ N^2 + .01199\ IN$	.9275	97.158
(2) Mesa, Laveen clay loam—1972.		
(.000) (.000) (.045) (.979) (.000)		
$Y = 3307.56230 + 128.58427\ I - 1.15371\ I^2 - 8.30055\ N + .00017\ N^2 + .11120\ IN$	.5834	10.643
(3) Yuma Valley, Glenbar silty clay loam—1971.		
(.006) (.035) (.000) (.002) (.035)		
$Y = 9906.58750 - 156.20261\ I + .88915\ I^2 + 16.68638\ N - .02387\ N^2 - .08777\ IN$	.8261	36.114
(4) Yuma Valley, Glenbar silty clay loam—1972.		
(.001) (.000) (.000) (.014) (.008)		
$Y = 503.09664 + 137.79631\ I - 1.23134\ I^2 + 22.14380\ N - .03077\ N^2 - .12260\ IN$	.7783	42.127
(5) Yuma Mesa, Superstitution fine sand—1971.		
(.092) (.103) (.000) (.000) (.000)		
$Y = 2406.35480 - 69.53114\ I + .50935\ I^2 + 29.31487\ N - .02643\ N^2 - .20324\ IN$	.9117	78.505
(6) Yuma Mesa, Superstitution fine sand—1972.		
(.011) (.015) (.000) (.000) (.000)		
$Y = 5230.07030 - 159.09475\ I + 1.15596\ I^2 + 46.39135\ N - .06134\ N^2 - .28697\ IN$	.8132	52.233

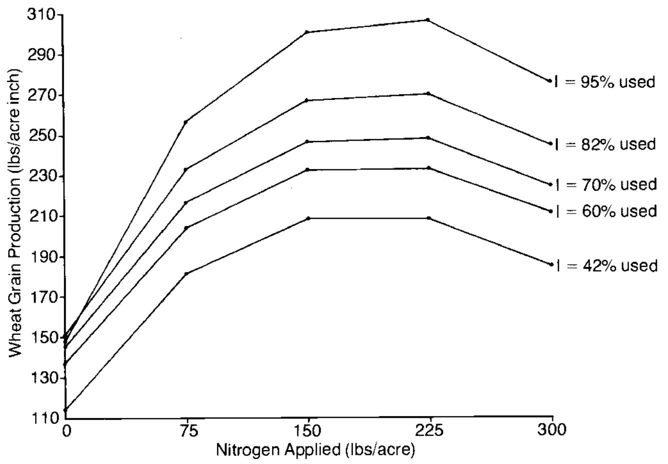
[1] Significance of estimated coefficient values, i.e., .000 is significant to less than .001% probability level. I = percent soil moisture use level when irrigated and N = nitrogen fertilizer and/or soil nitrogen in pounds N per acre.

pleted in the first three feet with a total of 32 inches of applied water and 225 pounds of N. Lowest expected yield and lowest water use result, for all N levels, when water is withheld until 95% of the available soil moisture is used. Maximum yield expectancy (6500 lbs/acre) for the 95% water use level is with 225 lbs N, but with only 21.5 inches of water.

Water use efficiency curves plotted in Figure 3 show that water use efficiency is a quadratic function curve.

FIGURE 3

Water use efficiency in wheat grain production for varying nitrogen and irrigation treatments, Mesa, 1971.

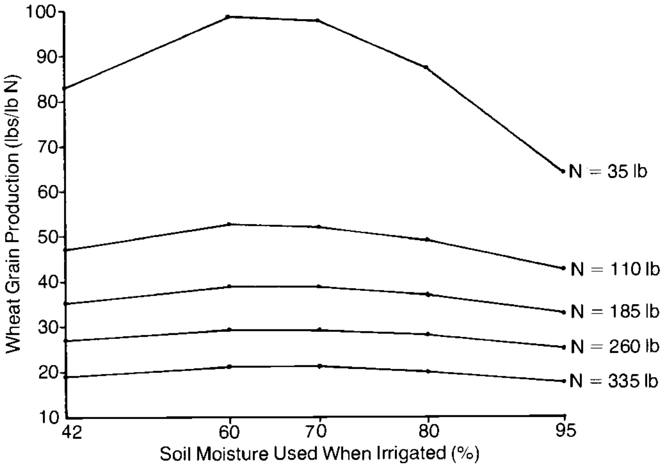


Source: Appendix Tables A-1 and A-3.

Maximum efficiency of 306 lbs of wheat grain with each inch of water resulted when irrigation was delayed until 95% of the moisture in the first three feet was depleted. Relative nitrogen use curves in Figure 4 show that nitrogen efficiency is inversely related to quantity of nitrogen available and, in a lesser degree, directly related to irrigation scheduling. Nitrogen use efficiency was greatest with irrigation when available soil moisture was 60 to 70% used.

FIGURE 4

Nitrogen use efficiency in wheat grain production for varying nitrogen and irrigation treatments, Mesa, 1971.[1]



[1]Assuming 35 pounds of residual soil nitrogen.

Source: Appendix Table A-1.

Although maximum efficiency (output/input) is an important evaluation when inputs are of high cost and/or scarce, economically the optimum use of an input occurs somewhere between maximum yield per unit of input (average product) and maximum yield (total product). Profits are maximized when the marginal product × price of wheat = per unit cost of input. (Marginal product is the addition to total output resulting from increasing the use-level of a production input by one increment.)

Determination of the optimum economical use inputs of water and nitrogen are usually made from estimates of the marginal physical products. The marginal products per increment of irrigation and nitrogen fertilizer are obtained from derivatives of the response function (Table 12, Equation 1) and are given in the following two equations:

$$\frac{\partial Y}{\partial I} = 160.11296 - 2.504241 + .01199N$$

$$\frac{\partial Y}{\partial N} = 37.61638 + .011991 - .17478N$$

Each of the marginal product equations contains both the irrigation and nitrogen terms because of the interactions between the two inputs. The marginal product of each of the variable inputs also depends on the levels at which the other input is applied.

When the marginal product equations are each set to equal 0 and solved simultaneously for I and N, we find that irrigation at 65% soil moisture use and application of 220 pounds of nitrogen is the input combination that gives the maximum yield. By inserting these values into Equation 1, Table 12, the maximum yield is calculated at 7672 pounds of wheat grain per acre.

The marginal physical products for nitrogen fertilizer use are tabulated in Table 13. The levels and timing of irrigation treatments were designed to maintain soil moisture tension at or below selected levels throughout the growing season and the data were analyzed on that basis. Because of this, the water increments (percent available soil moisture used when irrigated) are in reverse order to the conventional inches of water presentation. The negative marginal product values indicate diminishing total yield with increasing increments of nitrogen.

TABLE 13

Marginal product of applied nitrogen in wheat production for specified soil moisture and nitrogen use levels, Mesa, Arizona, 1971.

Soil Moisture (% Used)	Nitrogen Applied in Fertilizer (Lbs/Acre)				
	0	75	150	225	300
0	37.6	24.5	11.4	−1.7	−14.8
42	38.1	25.0	11.9	−1.2	−14.3
60	38.3	25.2	12.1	−1.0	−14.1
70	38.5	25.3	12.2	−0.9	−14.0
82	38.6	25.5	12.4	−0.7	−13.8
95	38.8	25.6	12.5	−0.6	−13.7

The marginal products for irrigation, Table 14, are also calculated and presented on the basis of percent soil moisture use rather than the usual inches of water applied. Predicted inches of water use for each irrigation and nitrogen level, as taken from Table A-3, are in parentheses to the marginal product for soil moisture use. By interpolation, 31.9 inches of water is the predicted requirement for the maximum yield (7642 lbs) input. As drier soil moisture regimes were effected, diminishing total yield occurred, but with less water use.

TABLE 14

Marginal product of percent soil moisture use in wheat production for specified soil moisture and nitrogen use levels, Mesa, Arizona, 1971.

Soil Moisture (% Used)	Nitrogen Applied in Fertilizer (Lbs/Acre)				
	0	75	150	225	300
0	160.1	161.0	161.9	162.8	163.7
42	54.9(25.0 ")[1]	55.8(28.8 ")	56.7(31.6 ")	57.6(33.6 ")	58.5(34.6 ")
60	9.9(24.9 ")	10.8(28.4 ")	11.7(31.0 ")	12.6(32.7 ")	13.5(33.5 ")
70	−15.2(23.4 ")	−14.3(26.8 ")	−13.4(29.2 ")	−12.5(30.8 ")	−11.6(31.4 ")
82	−45.2(20.2 ")	−44.3(23.4 ")	−43.4(25.7 ")	−42.5(27.1 ")	−41.6(27.6 ")
95	−77.8(15.1 ")	−76.9(18.1 ")	−76.0(20.3 ")	−75.1(21.5 ")	−74.2(21.7 ")

[1] Predicted inches of water required for maintaining the specified soil moisture use level to secure the corresponding marginal product. As irrigation was delayed for desired soil moisture tension levels less total water was applied.

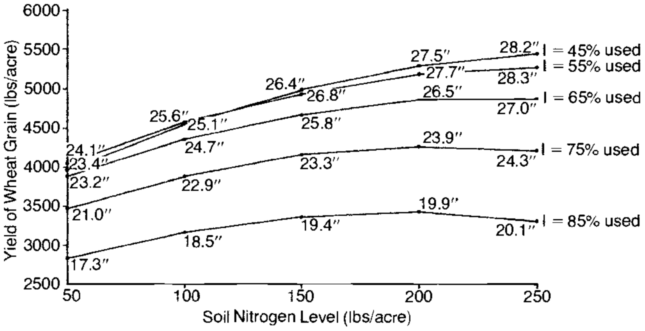
YUMA VALLEY

The Quadratic production functions of the Yuma Valley experiments, Equations 3 and 4, Table 12, were similar in R^2 value, F-ratio for overall regression and significant levels of the regression coefficients. All are good. Inputs of water and nitrogen in the 1971 experiment were higher than in the 1972 experiment. Because of the seemingly excessive amounts of irrigation water applied in 1971 and the unknown residual N from the previous crop (Table 8), the 1972 data were selected as the most representative and useful for predicting yield response from given irrigation and nitrogen inputs. About 78% of the variation in grain yield is explained by the amounts of irrigation and nitrogen applied. The F-ratio for overall regression is highly significant and the significance of the regression coefficients are very good, N^2 being the least significant at near the 1% level of significance.

Yield predictions obtained by inserting the nitrogen and water inputs into the equation and solving for the yield estimate are found in Appendix Table A-6. Individual response curves derived from these estimates are plotted in Figure 5. Irrigation water necessary to secure this response as predicted from delivery efficiency of this experiment (Appendix Table A-8) is also shown. Within the range of this experiment, maximum yields are predicted for irrigation at the 45-55% level of available soil moisture use, with inputs of 28 inches of water and 250 lbs N. Lowest expected yields and lowest water use occurred when irrigation was delayed until 85% of the soil moisture was depleted.

FIGURE 5

Wheat grain production as related to varying soil nitrogen levels and soil moisture use, Yuma Valley, 1972.

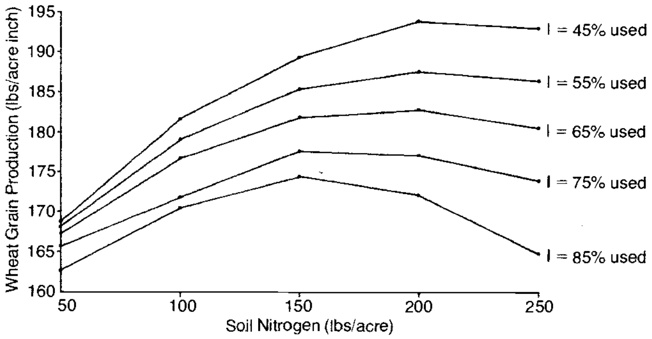


Source: Appendix Tables A-6 and A-8.

Water use efficiency curves (Figure 6) indicate that when water is scheduled for the 45% level of depletion, maximum efficiency of 194 lbs grain per inch of water can be expected from an input of 200 lbs N. When irrigation is delayed until available soil moisture is 85% used, 174.5 lbs wheat grain per inch of water can be expected from 150 lbs N. The nitrogen use efficiency curves in Figure 7, show the lower rates of nitrogen to be more efficient in production. As irrigation is delayed beyond 55% of available soil moisture used, decreasing efficiency may be expected. Optimum economical inputs can be determined with marginal product calculations similar to those indicated for the 1971 Mesa experiment.

FIGURE 6

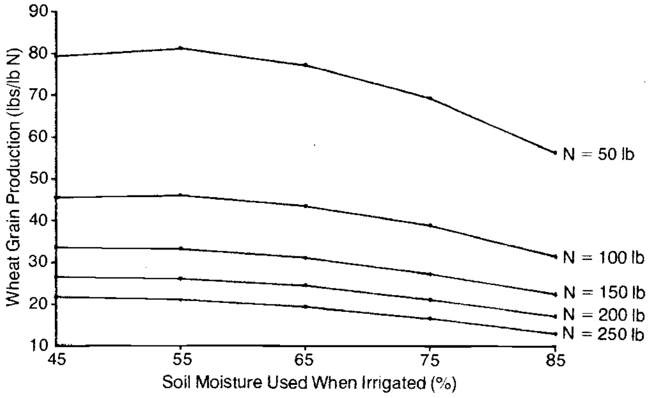
Water use efficiency in wheat grain production for varying nitrogen and irrigation treatments, Yuma Valley, 1972.



Source: Appendix Tables A-6 and A-8.

FIGURE 7

Nitrogen use efficiency in wheat grain production for varying nitrogen and irrigation treatments, Yuma Valley, 1972.



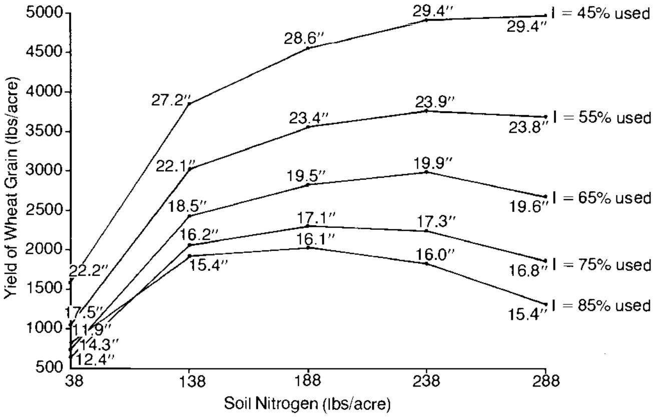
Source: Appendix Table A-6.

YUMA MESA

Although the R^2 and the F-ratio for overall regression were higher for the 1971 Yuma Mesa yield function (Table 12, Equation 5), the 1972 experiment (Table 12, Equation 6) was judged the most suitable for yield predictions because of the higher level of production, more efficient water use and the high level of significance found in the regression coefficients, which are all below the two percent level of probability. The F-ratio for overall regression was highly significant with 81% of the grain yield variation explained by varying levels of soil nitrogen and irrigation. Yield estimates derived by the production function are recorded in Appendix Table A-10. Predicted response curves for five levels of soil moisture use and five levels of nitrogen fertilization are plotted in Figure 8. Acre-inches of water, as estimated in Appendix Table A-12, are indicated on the water use curves for each nitrogen fertility level.

FIGURE 8

Wheat grain production as related to varying soil nitrogen levels and soil moisture use, Yuma Mesa, 1972.



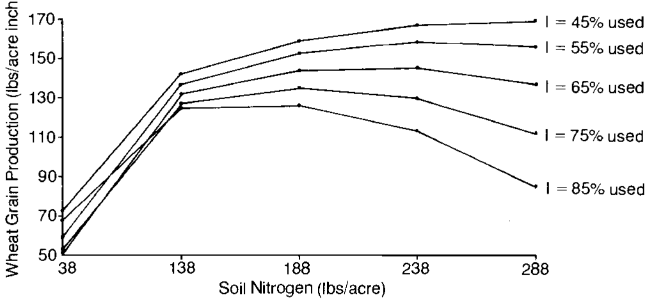
Source: Appendix Tables A-10 and A-12.

Maximum wheat grain yield prediction (4965 lbs/acre) was for the very wet irrigation treatment (45% of the available soil moisture used) with 288 lbs nitrogen and 29.4 inches of water. In contrast, when 85% available soil moisture was used before irrigation, peak grain production was 2026 lbs/acre from 16.1 inches of water and 188 lbs N and 1926 lbs/acre from 15.4 inches of water and 138 lbs N.

Water use efficiency curves in this experiment (Figure 9) were similar for all irrigation treatments and 138 lbs N per acre (127 to 142 lbs grain per inch of water). Beyond that point water use efficiency increased as the nitrogen level was increased to 169 lbs/inch for the very wet treatment (29.4 inches of water) and decreased with added nitrogen to 85 lbs/inch for the very dry treatment (15.4 inches of water). The nitrogen use efficiency curves in Figure 10 indicate lower rates of nitrogen to be more efficient in grain production. With the exception of the lowest input (38 lbs N), nitrogen use is progressively less efficient as the irrigation treatments become drier.

FIGURE 9

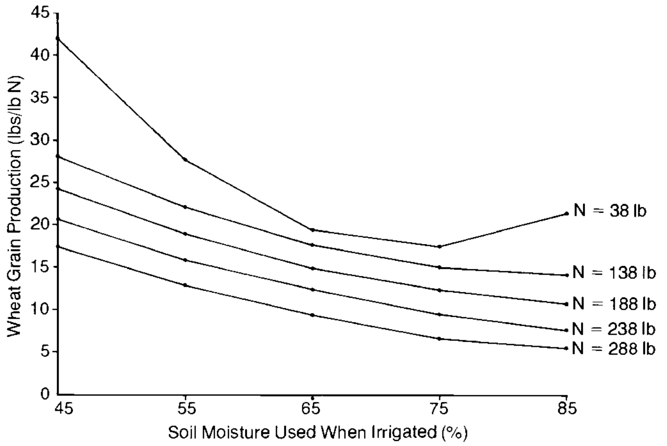
Water use efficiency in wheat grain production for varying nitrogen and irrigation treatments, Yuma Mesa, 1972.



Source: Appendix Tables A-10 and A-12.

FIGURE 10

Nitrogen use efficiency in wheat grain production for varying nitrogen and irrigation treatments, Yuma Mesa, 1972.

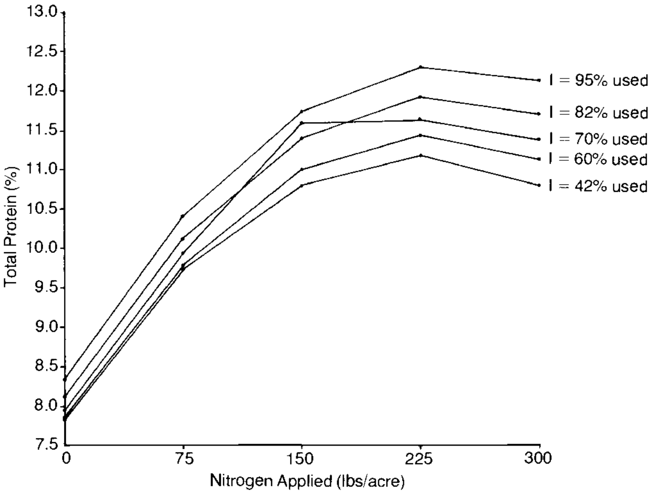


Source: Appendix Table A-10.

Quality response can also be estimated from input-output data. Wheat grain protein production function and predicted percentage values are given in Appendix Table A-13 for Mesa, 1971. The curves in Figure 11 illustrate the percent protein response surface for five levels of nitrogen as irrigation is held constant at five levels of soil moisture use. The highest grain protein percent is predicted for the 225 lbs nitrogen application and the driest irrigation regimes, indicating that plants growing in drier soils are able to compensate for decreases in nitrogen utilization due to lower yields by converting nitrogen to higher concentrations of protein in the grain. Similar quality response curves can be developed from the predicted values tabulated for total protein in Appendix Tables A-14 to A-18.

FIGURE 11

Wheat grain protein as related to varying soil nitrogen treatments and levels of soil moisture use.



Source: Appendix Table A-13.

SUMMARY

The functional relationships existing in controlled experiments involving irrigation water and nitrogen fertilizer variables are presented in a randomized complete block design having only 13 treatment combinations of a full 5 × 5 factorial. The basic response data were analyzed by multiple regression techniques to obtain curvilinear response surfaces of quadratic production functions for three locations with different soil characteristics. Adequate soil moisture and available nitrogen are factors of major importance for wheat nutrition. A maximum yield calculation of 7642 lbs per acre was obtained for the 1971 Mesa experiment with a soil moisture use level of 65% and 220 lbs of applied N, plus an unknown amount of residual soil nitrogen. The water requirement was 32 inches.

Although yields for the Yuma experiments were lower and not maximized, the highest yield prediction for each experiment was from the highest nitrogen level (250–300 lbs N) and at the highest level of soil moisture (45% used). Irrigation water required was in the general range of 28 to 40 inches.

Soil moisture determinations were generally confined to the top three feet of soil and the wheat plant is known to utilize moisture from a depth of five to six feet. Accurate estimates of residual soil nitrogen are difficult and in two instances non-existent in these tests. Irrigation and fertilizer application efficiency are often quite variable. Such factors place some limits on the validity of the production functions obtained, particularly when they are transposed to other environments or types of management.

Information from analyses such as these is useful in production planning and for efficient utilization of resources. As irrigation water and fertilizer become more costly and scarce because of increased production demands, reallocation of water for urban use, and diversion of energy to uses other than for making fertilizer, estimates of input-output response become more meaningful and necessary.

Economists and crop and soil scientists can use these response functions for calculating economic water and nitrogen use alternatives as related to soil type, production levels, alternative crops, and in land use planning.

APPENDIX

TABLE A-1

Predicted wheat grain production in lbs per acre for percentage of available soil moisture depleted before irrigation and lbs of nitrogen applied to Laveen clay loam at Mesa, Arizona in 1971.[1]

Available Soil Moisture (% used)	Nitrogen Fertilizer Applied (lbs N/acre)[2]				
	0	75	150	225	300
42	2853	5221	6605	7006	6424
60	3436	5820	7220	7638	7072
70	3410	5802	7212	7638	7081
82	3047	5451	6871	7308	6772
95	2247	4663	6095	6543	6009

[1] Source: Quadratic production function =

$$-1662.94270 + \overset{(.000)}{160.11296\ I} - \overset{(.000)}{1.25212\ I^2}$$

$$+\overset{(.000)}{37.61638\ N} - \overset{(.000)}{.08739\ N^2} + \overset{(.718)}{.01199\ IN}$$

$R^2 = .9275 \qquad F = 97.158$

[2] Does not include residual N carry-over from previous crop.

TABLE A-2

Predicted wheat grain production in lbs per acre for percentage of available moisture depleted before irrigation and lbs of soil nitrogen for Laveen clay loam at Mesa, Arizona in 1972[1]

Available Soil Moisture (% used)	Soil Nitrogen (lbs N/acre)[2]				
	125	205	285	365	445
42	6126	5822	5521	5221	4924
60	6668	6543	6419	6297	6178
70	6593	6556	6522	6489	6459
82	6199	6269	6341	6415	6491
95	5396	5582	5770	5960	6152

[1] Source: Quadratic production function =

$$3307.56230 + \overset{(.000)}{128.58427\ I} - \overset{(.000)}{1.15371\ I^2}$$

$$-\overset{(.045)}{8.30055\ N} + \overset{(.979)}{.00017\ N^2} + \overset{(.000)}{.11120\ IN}$$

$R^2 = .5834 \qquad F = 10.643$

[2] Includes applied N plus residual N calculated from soil analyses to a depth of four feet.

TABLE A-3

Predicted acre inches of water needed in wheat grain production for percentage of available soil moisture depleted before irrigating and lbs of nitrogen applied to Laveen clay loam at Mesa, Arizona in 1971.[1]

Available Soil Moisture (% used)	Nitrogen Fertilizer Applied (lbs N/acre)[2]				
	0	75	150	225	300
42	25.00	28.76	31.62	33.58	34.62
60	24.91	28.42	31.03	32.72	33.51
70	23.41	26.78	29.24	30.80	31.44
82	20.24	23.44	25.73	27.12	27.60
95	15.13	18.14	20.25	21.45	21.74

[1] Source: Quadratic production function =

$$12.15034 + \overset{(.000)}{.52360\ I} - \overset{(.000)}{.00518\ I^2}$$

$$+ \overset{(.000)}{.06420\ N} - \overset{(.001)}{0.00008\ N^2} - \overset{(.046)}{0.00019\ IN}$$

$R^2 = .9449$ F = 129.323

[2] Does not include residual N carry-over from previous crop.

TABLE A-4

Predicted acre inches of water needed in wheat grain production for percentage of available soil moisture depleted before irrigation and lbs of soil nitrogen for Laveen clay loam at Mesa, Arizona in 1972.[1]

Available Soil Moisture (% used)	Soil Nitrogen (lbs N/acre)[2]				
	125	205	285	365	445
40	30.04	33.17	35.36	36.60	36.91
60	28.70	31.67	33.70	34.79	34.94
70	26.66	29.56	31.51	32.53	32.60
82	23.01	25.82	27.68	28.60	28.58
95	17.59	20.29	22.05	22.87	22.75

[1] Source: Quadratic production function =

$$14.55881 + \overset{(.002)}{.39959\ I} - \overset{(.000)}{.00455\ I^2}$$

$$+ \overset{(.000)}{.06726\ N} - \overset{(.007)}{.00007\ N^2} - \overset{(.388)}{.00010\ IN}$$

$R^2 = .9094$ F = 76.264

[2] Includes applied N plus residual N calculated from soil analyses to a depth of four feet.

TABLE A-5

Predicted wheat grain production in lbs per acre for five levels of available soil water depletion before irrigation and five levels of nitrogen applied to Glenbar silty clay loam in the Yuma Valley in 1971.[1]

Available Soil Moisture (% used)	Nitrogen Fertilizer Applied (lbs N/acre)[2]				
	0	75	150	225	300
45	4678	5499	6051	6335	6351
55	4005	4760	5247	5465	5414
65	3510	4199	4620	4772	4656
75	3193	3816	4171	4258	4076
85	3053	3611	3900	3921	3673

[1] Source: Quadratic production function =

$$9906.58750 - \overset{(.006)}{156.20261\ I} + \overset{(.035)}{.88915\ I^2}$$

$$+ \overset{(.000)}{16.68638\ N} - \overset{(.002)}{.02387\ N^2} - \overset{(.035)}{.08777\ IN}$$

$R^2 = .8261$ F = 36.114

[2] Does not include residual N carry-over from previous crop.

TABLE A-6

Predicted wheat grain production in lbs per acre for five levels of available moisture depletion before irrigation and five levels of soil nitrogen for Glenbar silty clay loam in Yuma Valley, 1972.[1]

Available Soil Moisture (% used)	Soil Nitrogen (lbs N/acre)[2]				
	50	100	150	200	250
45	3959	4559	5006	5299	5438
55	4044	4583	4969	5200	5278
65	3883	4361	4685	4855	4872
75	3476	3893	4155	4264	4219
85	2822	3178	3379	3427	3321

[1] Source: Quadratic production function =

$$503.09664 + \overset{(.001)}{137.79631\ I} - \overset{(.000)}{1.23134\ I^2}$$

$$+ \overset{(.000)}{22.14380\ N} - \overset{(.014)}{.03077\ N^2} - \overset{(.008)}{.12260\ IN}$$

$R^2 = .7783$ F = 42.127

[2] Includes applied N plus residual N calculated from soil analyses to a depth of three feet.

TABLE A-7

Predicted acre inches of water required in wheat grain production for five levels of available soil moisture depletion before irrigation and five levels of nitrogen applied to Glenbar silty clay loam in Yuma Valley, 1971.[1]

Available Soil Moisture (% used)	Nitrogen Fertilizer Applied (lbs N/acre)[2]				
	0	75	150	225	300
45	46.52	47.03	47.34	47.44	47.34
55	38.89	39.35	39.62	39.67	39.52
65	33.15	33.57	33.78	33.79	33.60
75	29.31	29.68	29.85	29.81	29.57
85	27.37	27.69	27.81	27.73	27.44

[1] Source: Quadratic production function =

$$104.30968 - \overset{(.000)}{1.71081\ I} + \overset{(.000)}{.00948\ I^2}$$

$$+ \overset{(.124)}{.01101\ N} - \overset{(.223)}{.00002\ N^2} - \overset{(.445)}{.00006\ IN}$$

$R^2 = 0.9859$ F = 533.085

[2] Does not include residual N carry-over from previous crop (estimation—50 lbs).

TABLE A-8

Predicted acre inches of water required in wheat grain production for five levels of available soil moisture depletion before irrigation and five levels of soil nitrogen for Glenbar silty clay loam in Yuma Valley, 1972.[1]

Available Soil Moisture (% used)	Soil Nitrogen (lbs N/acre)[2]				
	50	100	150	200	250
45	23.44	25.09	26.44	27.47	28.18
55	24.05	25.59	26.81	27.72	28.32
65	23.23	24.65	25.75	26.54	27.02
75	20.99	22.86	23.27	23.94	24.29
85	17.32	18.49	19.36	19.91	20.14

[1] Source: Quadratic production function =

$$.50444 + \overset{(.000)}{.78710\ I} - \overset{(.000)}{.00714\ I^2}$$

$$+ \overset{(.000)}{.05333\ N} - \overset{(.007)}{.00006\ N^2} - \overset{(.005)}{.00024\ IN}$$

$R^2 = .9497$ F= 226.458

[2] Includes applied N plus residual N calculated from soil analyses to a depth of three feet.

TABLE A-9

Predicted wheat grain production in lbs per acre for five levels of available soil moisture depleted before irrigation and five levels of nitrogen applied to Superstitution fine sand on the Yuma Mesa in 1971.[1]

Available Soil Moisture (% used)	Nitrogen Fertilizer Applied (lbs N/acre)[2]				
	25	100	175	250	325
45	797	2061	3029	3699	4072
55	560	1672	2487	3005	3225
65	425	1385	2048	2413	2481
75	392	1199	1710	1922	1838
85	461	1116	1474	1534	1297

[1] Source: Quadratic production function =

$$2406.35480 - \overset{(.092)}{69.53114}\ I + \overset{(.103)}{.50935}\ I^2$$

$$+ \overset{(.000)}{29.31487}\ N - \overset{(.000)}{.02643}\ N^2 - \overset{(.000)}{.20324}\ IN$$

$R^2 = .9117$ $F = 78.505$

[2] Does not include residual N carry-over from previous crop (estimated near 0).

TABLE A-10

Predicted wheat grain production in lbs per acre for five levels of available soil moisture depleted before irrigation and five levels of soil nitrogen for Superstitution fine sand on the Yuma Mesa in 1972.[1]

Available Soil Moisture (% used)	Soil Nitrogen (lbs N/acre)[2]				
	38	138	188	238	288
45	1595	3863	4537	4905	4965
55	1051	3032	3563	3787	3704
65	738	2432	2820	2900	2673
75	657	2064	2307	2244	1874
85	806	1926	2026	1820	1306

[1] Source: Quadratic production function =

$$5230.07030 - \overset{(.011)}{159.09475}\ I + \overset{(.015)}{1.15596}\ I^2$$

$$+ \overset{(.000)}{46.39135}\ N - \overset{(.000)}{.06134}\ N^2 - \overset{(.000)}{.28697}\ IN$$

$R^2 = .8132$ $F = 52.233$

[2] Includes applied N plus minimal residual N calculated from soil analyses to a depth of three feet.

TABLE A-11

Predicted acre inches of water required in wheat grain production for five levels of available soil moisture depletion before irrigation and five levels of nitrogen applied to Superstitution fine sand on Yuma Mesa in 1971.[1]

Available Soil Moisture (% used)	Nitrogen Fertilizer Applied (lbs N/acre)[2]				
	25	100	175	250	325
45	40.82	41.41	41.85	42.16	42.33
55	33.42	33.97	34.37	34.64	34.76
65	27.88	28.39	28.75	28.97	29.05
75	24.21	24.67	24.99	25.17	25.21
85	22.39	22.81	23.08	23.22	23.22

[1] Source: Quadratic production function =

$$96.83880 - \overset{(.000)}{1.66845}\ I + \overset{(.000)}{.00930}\ I^2$$

$$+ \overset{(.000)}{.01192}\ N - \overset{(.035)}{0.00001}\ N^2 - \overset{(.080)}{0.00006}\ IN$$

$R^2 = .9977$ $F = 3306.679$

[2] Does not include residual N carry-over from previous crop (estimated near 0).

TABLE A-12

Predicted acre inches of water required in wheat grain production for five levels of available soil moisture before irrigation and five levels of soil nitrogen for Superstitution fine sand on the Yuma Mesa in 1972.[1]

Available Soil Moisture (% used)	Soil Nitrogen (lbs N/acre)[2]				
	38	138	188	238	288
45	22.22	27.18	28.61	29.35	29.40
55	17.53	22.12	23.37	23.92	23.78
65	14.25	18.46	19.52	19.89	19.57
75	12.37	16.20	17.08	17.27	16.75
85	11.89	15.35	16.05	16.04	15.35

[1] Source: Quadratic production function =

$$57.43736 - \overset{(.000)}{1.15639}\ I + \overset{(.000)}{.00702}\ I^2$$

$$+ \overset{(.000)}{.09075}\ N - \overset{(.000)}{.00014}\ N^2 - \overset{(.004)}{.00037}\ IN$$

$R^2 = .9310$ $F = 161.865$

[2] Includes applied N plus minimal residual N calculated from soil analyses to a depth of three feet.

TABLE A-13

Predicted wheat grain protein content for percentages of available soil moisture depleted before irrigation and lbs of nitrogen applied to Laveen clay loam at Mesa, Arizona in 1971.[1]

Available Soil Moisture (% used)	Nitrogen Fertilizer Applied (lbs N/acre)[2]				
	0	75	150	225	300
42	7.82	9.69	10.81	11.18	10.81
60	7.87	9.81	11.00	11.44	11.13
70	7.95	9.93	11.61	11.64	11.37
82	8.11	10.13	11.41	11.93	11.71
95	8.33	10.41	11.73	12.31	12.13

[1] Source: Quadratic production function =

$$8.18435 - \overset{(.561)}{.01696}\ I + \overset{(.354)}{.00020}\ I^2$$

$$+ \overset{(.000)}{.02783}\ N - \overset{(.000)}{.00007}\ N^2 + \overset{(.074)}{.00005}\ IN$$

$R^2 = .9307$ $F = 102.130$

[2] Does not include residual N carry-over from previous crop.

TABLE A-14

Predicted wheat grain protein content for percentage of available soil moisture depleted before irrigation and lbs of soil nitrogen for Laveen clay loam at Mesa Arizona in 1972.[1]

Available Soil Moisture (% used	Soil Nitrogen (lbs N/acre)[2]				
	125	205	285	365	445
42	10.88	11.75	12.32	12.58	12.53
60	10.87	11.69	12.20	12.34	12.28
70	11.00	11.78	12.26	12.43	12.29
82	11.26	12.01	12.45	12.58	12.40
95	11.68	12.39	12.79	12.88	12.66

[1] Source: Quadratic production function =

$$9.70989 - \overset{(.199)}{.03747}\ I + \overset{(.046)}{.00042}\ I^2$$

$$+ \overset{(.000)}{.02046}\ N - \overset{(.000)}{.00002}\ N^2 - \overset{(.161)}{.00004}\ IN$$

$R^2 = .6657$ $F = 15.135$

[2] Includes applied N plus residual N calculated from soil analyses to a depth of four feet.

TABLE A-15

Predicted wheat protein percent for five levels of available soil moisture depletion before irrigation and five levels of nitrogen applied to Glenbar silty clay loam in the Yuma Valley, 1971.[1]

Available Soil Moisture (% used)	Nitrogen Fertilizer Applied (lbs N/acre)[2]				
	0	75	150	225	300
45	8.96	11.23	12.89	13.96	14.42
55	9.04	11.26	12.88	13.90	14.32
65	9.22	11.40	12.98	13.95	14.32
75	9.52	11.66	13.19	14.11	14.44
85	9.93	12.02	13.50	14.39	14.67

[1] Source: Quadratic production function =

$$9.95555 - \overset{(.712)}{.04674}\, I + \overset{(.572)}{.00055}\, I^2$$

$$+ \overset{(.000)}{.03699}\, N - \overset{(.003)}{.00005}\, N^2 - \overset{(.526)}{.00006}\, IN$$

$$R^2 = .7869 \qquad F = 28.061$$

[2] Does not include residual N carry-over from previous crop (estimation—50 lbs).

TABLE A-16

Predicted wheat grain protein percent for five levels of available soil moisture before irrigation and five levels of soil nitrogen for Glenbar silty clay loam in Yuma Valley, 1972.[1]

Available Soil Moisture (% used)	Soil Nitrogen (lbs N/acre)[2]				
	50	100	150	200	300
45	11.97	12.47	12.96	13.46	13.95
55	12.05	12.59	13.12	13.65	14.18
65	12.24	12.81	13.38	13.95	14.51
75	12.52	13.13	13.74	14.35	14.95
85	12.92	13.57	14.21	14.86	15.50

[1] Source: Quadratic production function =

$$12.55983 - \overset{(.592)}{.04762}\, I + \overset{(.438)}{.00052}\, I^2$$

$$+ \overset{(.518)}{.00063}\, N - \overset{(.985)}{.000001}\, N^2 + \overset{(.444)}{.00008}\, IN$$

$$R^2 = .5385 \qquad F = 14.002$$

[2] Includes applied N plus residual N calculated from soil analyses to a depth of three feet.

TABLE A-17

Predicted wheat grain protein percent for five levels of available soil moisture depleted before irrigation and five levels of nitrogen applied to Superstitution fine sand on the Yuma Mesa in 1971.[1]

Available Soil Moisture (% used)	Nitrogen Fertilizer Applied (lbs N/acre)[2]				
	25	100	175	250	325
45	7.77	10.06	11.43	11.85	11.35
55	9.09	11.59	13.15	13.78	13.48
65	9.77	12.47	14.23	15.07	14.97
75	9.81	12.71	14.68	15.71	15.82
85	9.21	12.31	14.48	15.72	16.03

[1] Source: Quadratic production function =

$$-6.73111 + \overset{(.177)}{.44457}\, I - \overset{(.201)}{.00320}\, I^2$$

$$+ \overset{(.205)}{.02873}\, N - \overset{(.066)}{.00008} + \overset{(.271)}{.00027}\, IN$$

$$R^2 = .4756 \qquad F = 6.892$$

[2] Does not include residual N carry-over from previous crop (estimated near 0).

TABLE A-18

Predicted wheat grain protein percent for five levels of available soil moisture depletion before irrigation and five levels of soil nitrogen in Superstitution fine sand on the Yuma Mesa, 1972.[1]

Available Soil Moisture (% used)	Soil Nitrogen (lbs N/acre)[2]				
	38	138	188	238	288
45	7.80	11.23	12.26	12.83	12.95
55	8.71	12.29	13.40	14.04	14.23
65	9.29	13.03	14.21	14.93	15.20
75	9.56	13.44	14.70	15.50	15.84
85	9.50	13.54	14.87	15.75	16.17

[1] Source: Quadratic production function =

$$-1.77475 + \overset{(.072)}{.24560}\, I - \overset{(.118)}{.00161}\, I^2$$

$$+ \overset{(.000)}{.04353}\, N - \overset{(.001)}{.00009}\, N^2 + \overset{(.206)}{.00015}\, IN$$

$$R^2 = .7758 \qquad F = 41.517$$

[2] Includes applied N plus minimal residual N calculated from soil analyses to a depth of three feet.

TABLE A-19

Summary of soils data for Mesa experiments.

	Depth of Sample			
	0–1′	1–2′	2–3′	3–4′
Particle Size—				
Sand (%)	52.0	60.0	61.0	58.0
Silt (%)	27.2	27.0	25.0	24.5
Clay (%)	20.8	13.0	14.0	17.5
Organic Matter (%)	.85	.41	.19	.14
pH (paste)	7.90	8.10	8.15	8.10
Soluble Salts in Sat. Ext. ($EC_e \times 10^3$)	1.52	1.06	0.96	1.06
ML EDTA	0.69	0.41	0.36	0.38
ESP	3.6	3.4	6.0	6.3
CEC (meq/100 g)	17.8	10.9	9.2	8.8
Cations and Anions of Saturation Extract (ppm)				
PO_4	2.92	0.40	0.25	0.30
Potassium	9.6	4.0	3.5	2.9
Calcium	96.0	70.0	60.0	50.0
Magnesium	25.5	7.3	7.3	15.8
Sodium	190.0	151.0	146.0	135.0
Chloride	600.0	550.0	600.0	600.0
Sulfate	175.0	175.0	175.0	200.0
Carbonate	0.0	0.0	0.0	0.0
Bicarbonate	305.0	244.0	366.0	366.0
Available Water Holding Capacity (in/4′)	7.3			

TABLE A-20

Summary of soils data for the Yuma Valley experiments.

	Depth of Sample	
	0–1′	1–3′
Particle Size—		
Sand (%)	4.60	5.35
Silt (%)	66.70	66.85
Clay (%)	28.70	27.80
pH (paste)	7.85	7.78
Soluble Salts in Sat. Ext. ($EC_e \times 10^3$)	2.40	5.71
CEC (meq/100 g)	23.65	23.70
Cations and Anions of Saturation Extract (ppm)		
PO_4	4.95	.69
Potassium		
Calcium	183.0	176.13
Magnesium	50.65	172.13
Sodium	200.15	547.00
Chloride	412.30	879.13
Sulfate	718.30	2089.15
Carbonate	0.00	0.00
Bicarbonate	350.80	310.00
Available Water Holding Capacity (in/4′)	12.0	

TABLE A-21

Summary of soils data for the Yuma Mesa experiments.

	Depth of Sample		
	6–10″	18–22″	24–30″
Particle Size—			
Sand %	71.3	72.4	73.2
Silt %	21.0	20.4	19.7
Clay %	7.7	7.2	7.1
pH (paste)	8.00	7.93	7.95
Soluble Salts in Sat. Ext. ($EC_e \times 10^3$)	.97	1.60	2.00
CEC (meq/100 g)	5.0	4.6	4.3
Cations and Anions of Saturation Extract (ppm)			
Calcium	60.50	82.50	118.75
Magnesium	31.72	26.87	35.62
Sodium	110.15	170.15	259.75
Chloride	300.00	370.85	356.25
Sulfate	156.12	382.66	406.25
Carbonate	0.00	0.00	0.00
Bicarbonate	213.50	167.75	160.12
Available Water Holding Capacity (in/4′)	2.6		

TABLE A-22

Weather summary for Mesa wheat experiments, 1971 and 1972.

1971				1972			
Growth period 177 days	Temperature °F Daily Average		Rainfall inches	Growth period 182 days	Temperature °F Daily Average		Rainfall inches
	Max.	Min.			Max.	Min.	
Nov. 16–30	69	42	—	Nov. 19–30	70	40	.02
Dec. 1–31	66	37	.21	Dec. 1–31	62	37	.52
Jan. 1–31	68	34	.16	Jan. 1–31	67	34	—
Feb. 1–28	70	39	.35	Feb. 1–29	74	40	—
Mar. 1–31	78	44	—	Mar. 1–31	86	50	—
Apr. 1–30	81	49	.22	Apr. 1–30	85	51	—
May 1–10	83	51	—	May 1–18	93	57	—

TABLE A-23

Weather summary for Yuma Valley wheat experiment, 1971 and 1972.

1971				1972			
Growth Period 164 days	Temperature °F Daily Average		Rainfall Inches	Growth Period 146 days	Temperature °F Daily Average		Rainfall Inches
	Max.	Min.			Max.	Min.	
Dec. 11–31	66.2	38.1	.02	Dec. 17–31	65.6	40.1	.05
Jan. 1–31	69.7	37.3	.03	Jan. 1–31	68.4	34.4	—
Feb. 1–28	74.4	39.5	.01	Feb. 1–29	76.6	41.2	—
Mar. 1–31	79.7	43.6	—	Mar. 1–31	87.6	48.8	—
Apr. 1–30	81.6	48.5	.29	Apr. 1–30	86.5	50.5	—
May 1–25	87.7	55.0	—	May 1–11	92.3	54.5	—

TABLE A-24

Weather summary for Yuma Mesa wheat experiments, 1971 and 1972

1971				1972			
Growth Period 165 days	Temperature °F Daily Average Max.	Temperature °F Daily Average Min.	Rainfall Inches	Growth Period 152 days	Temperature °F Daily Average Max.	Temperature °F Daily Average Min.	Rainfall Inches
Dec. 9–31	66.4	37.3	T	Dec. 15–31	65.1	38.6	.03
Jan. 1–31	69.0	37.9	—	Jan. 1–31	68.2	34.3	—
Feb. 1–28	74.5	39.1	.03	Feb. 1–29	76.9	39.3	—
Mar. 1–31	80.5	43.4	—	Mar. 1–31	89.9	48.8	—
Apr. 1–30	83.2	49.1	.30	Apr. 1–30	88.8	50.0	—
May 1–24	88.4	52.9	.11	May 1–15	95.5	53.7	—

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