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Management alternatives for improved durum wheat production under supplemental irrigation in Syria

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Abstract

In the Mediterranean zone, efforts to optimize combinations of supplemental irrigation (SI), improved varieties, nitrogen (N) and sowing dates aim to improve and stabilize cereal yields and maintain quality, especially for durum wheat. Thus, a 4 year field study (1992/1993 to 1995/1996) on a deep clay soil in northern Syria assessed the impact of SI (rain-fed, 1/3, 2/3 and full SI) combined with variable N application rates (0, 50, 100, 150 kg ha^{-1}) and sowing date (early, normal, late) for four improved durum wheat varieties adapted to rain-fed and irrigated conditions. As rainfall and evapotranspiration varied over the 4 years, the amount of SI water required also varied. Yields varied with the season, and the main factors, except variety, were significant. Delaying sowing from November to January reduced yields and response to both SI and N. With irrigation, crop responses were generally significant up to 100 N ha^{-1}, whereas the optimum response for rain-fed conditions occurred with 50 kg N ha^{-1}. Limited SI (1/3) significantly increased yields, but almost maximum yields were obtained by 2/3 of full SI. Water- and N-use efficiencies were greatly increased by SI, with little variation among varieties. However, irrigation and delayed sowing decreased grain protein levels, which were partially compensated for by added N. A similar effect was observed for kernel vitreousness. Models developed from the response data can facilitate the potential transfer of these findings. Thus, in most growing seasons, minimum irrigation during the winter growing season, combined with appropriate fertilization, can enhance wheat output and yet maintain grain quality.

Keywords: Mediterranean climate; Nitrogen; Rain-fed cereals; Sowing date; Supplemental irrigation; Yield sustainability

1. Introduction

Agriculture in the West Asia–North Africa (WANA) region is primarily based on dryland cereals integrated with livestock production, mainly sheep (Cooper et al., 1987). The climate is mainly Mediterranean, with cool to cold winters, with rainfall from November to April and hot dry summers. Winters are milder along the coastal areas and are colder inland, merging towards a continental climate, and with increasing elevation. The annual rainfall is extremely variable, from year to year and within seasons, and can range from 50 to 1200 mm. However, most cropland is in the 200–600 mm range (Kassam, 1981); indeed, in Syria, it is mainly between 250 and 450 mm year^{-1}. Both rainfall and temperature dictate crop-growth duration and cropping systems, which change in response to the variation in both elevation and rainfall. Rainfall is inversely related

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to seasonal temperatures, which in turn influence evapotranspiration (Harris, 1995). With the first rain in October–November, evaporation and temperatures decrease; the January–February period, with the lowest mean temperatures (<5°C) and evaporative demand (<2 mm day^{-1}), coincides with peak rainfall. Frost is frequent, but snow is rare, especially in lowland areas. In early spring, evapotranspiration begins to exceed rainfall. The latter growth period is usually restricted by limited moisture.

Effective technology transfer to the region's farmers has to be based on a clear perception of the various constraints to crop production, leading to integrated cropping system recommendations that are consistent with socioeconomic conditions. As with many countries of the world in economic transition, any future production increases in Syria and WANA in general have to come from increased yields, with little opportunities for expansion of cropland. The sparse and precarious resources of the region, particularly water (Oweis, 1997), make this a daunting task.

The foremost concern in arid and semi-arid areas is water availability and how to optimize its use. The dominant constraint on wheat production is limited water, especially where a high evaporative demand coincides with low rainfall (Smith and Harris, 1981; Campbell et al., 1993a). Though crop yields under dryland conditions in WANA are related to seasonal rainfall, water-use efficiency (WUE) can be substantially improved by crop management practices (Cooper et al., 1987) and fertilizer use (Harmsen, 1984; Keatinge et al., 1985; Ryan and Matar, 1992). Whereas, formerly, virtually all cereal production was rain-fed, now up to 40% of the cereal-growing area is irrigated, primarily from surface waters, but increasingly from shallow groundwater. In Syria, irrigation accounts for 70% of cereal production. Farmers generally use small basins (50–100 m^2) to apply SI to wheat. This method, although labor-intensive, requires little or no capital investment. In areas where summer crops are irrigated, farmers have begun investing in sprinkler systems, which they also use for SI of winter crops. The introduction of supplemental irrigation (SI) to winter-grown cereals in Syria has stabilized and increased yields as well as improved water-use efficiency. With expansion in irrigation over the last years and water resources becoming scarcer, sustainable and improved production can only be maintained by improving WUE.

After drought, N is the major constraint in dryland cereal farming within the Mediterranean area (Harmsen, 1984; Anderson, 1985; Ryan et al., 1991; Mosseddaq and Smith, 1994). As fertilizer N responses are directly related to rainfall under dryland conditions in WANA (Ryan et al., 1991; Campbell et al., 1993b; Pala et al., 1996), N use should be correspondingly greater when SI is also applied. Potential yield increases in any environment depend not only on water and N (Aggarwal and Kalra, 1994) but also on cultivars (Anderson, 1985) and sowing time (O'Leary et al., 1985). Under Mediterranean climatic conditions, delaying sowing after the optimum time, November, which coincides with the onset of seasonal rains, consistently reduces yields (Photiades and Hadjichristodoulou, 1984; Stapper and Harris, 1989; Harris et al., 1991). In Syria, potential wheat yields are estimated to decline by 4.2% for each week of delay after early November sowing (Stapper and Harris, 1989).

Various studies of winter wheat in Mediterranean areas have highlighted the individual importance of water, N, sowing dates, and cultivars. The emerging significance of SI in Syria and in the WANA region underlines the need to integrate these factors. While yield is of prime concern in the food-deficit WANA region, quality is also a growing concern (Wrigley, 1994). In Syria, a minimum of 12% protein is required for export of durum wheat. Similarly, a higher degree of grain vitreousness is a quality criterion — the presence of 'yellow berry' is undesirable. Both protein and vitreousness are more influenced by the environment than genetics (Nachit et al., 1992). Consequently, management practices such as fertilization and irrigation can significantly influence quality traits, depending on the variety (Bulman and Smith, 1993; Webster and Jackson, 1993; Ryan et al., 1997b).

Since its inception in 1977, ICARDA has operated a number of agricultural research stations that focus on dryland crop research across the average rainfall gradient of about 200–600 mm $year^{-1}$. Wide inter-annual and inter-season rainfall variation is characteristic of the region. In such conditions, SI can have a large impact on yield in normal and dry years, but little or no irrigation is required in favorable years. Our objective was to identify, in a 4 year field trial (1992–1996), at ICARDA's main station, Tel Hadya, near Aleppo in northern Syria (mean annual rainfall, 330 mm), the most effective combinations of SI, N fertilizer, and sowing dates for enhanced yield and quality of four improved durum wheat varieties.

2. Materials and methods

2.1. Soil and weather

The soil at Tel Hadya station (Ryan et al., 1997a) is generally deep (over 1 m) and has a heavy clay texture (fine clay, montmorillonitic, thermic Calcixerollic Xerochrept). The relevant properties are as follows: pH 8.0; $CaCO_3$, 240 g kg^{-1}; organic matter, 8.4 g kg^{-1}; cation exchange capacity, 52 cmol kg^{-1} at the beginning of the trial, extractable potassium by 1 N ammonium acetate, pH 7.0 (546 mg kg^{-1}) well above the critical level, and low extractable phosphorus values (0.5 M $NaHCO_3$, <5 mg kg^{-1}) and mineral N (NO_3—N+NH_4—N) to a depth of 60 cm (<10 mg kg^{-1}). This clay soil has good structure and is well drained, with an infiltration rate of 11 mm h^{-1}. The mean soil moisture in the top 100 cm soil at the field capacity (−33 kPa) and at the permanent wilting point (−1500 kPa) is about 48 and 24% by volume, respectively. Throughout the growing season, the profile undergoes recharge from November to March and discharge from then until June (Harris, 1995). Only in above-normal rainfall years is the profile wetted below 1.5 m.

Rainfall was variable during the four growing seasons in total amount, i.e. 281 mm (1992/1993), 358 mm (1993/1994), 330 mm (1994/1995) and 395 mm (1995/1996) and in distribution (Table 1). The first season showed below-average rainfall (i.e. 330 mm). Following the first rain on 15 November, subsequent rain was well distributed until March; then, little effective rainfall occurred until 37 mm rainfall in May made a substantial contribution to crop yield. The rainfall in the second season was slightly above average, but was poorly distributed, with most of the rainfall in January–February and little thereafter; a heat wave occurred in April and May. The rainfall in the third year was about average, and was well distributed. The fourth year was above average and well distributed, but had higher temperatures during the grain-filling period.

2.2. Trial treatments and design

The treatments included:

1. three sowing dates, which varied depending on the year (early, mid-November; normal, mid-December; and late, mid-January);
2. four SI rates; rain-fed (no irrigation), full SI (irrigation to avoid moisture stress), and 1/3, and 2/3 of full SI.
3. Four N application rates (0, 50, 100, and 150 kg N ha^{-1}); and
4. Four high-yielding, widely adapted durum wheat varieties:

Cham *1*: resistant to yellow rust;
Lahn: irrigated areas, cold tolerant;
Cham 3: drought and heat tolerant, high grain quality for semolina products;
Omrabi 5: high drought tolerance, diverse environments.

A split-split-split plot design, with three replicates, was used. Sowing dates were represented by the main plots, varieties by the sub-plots, water rates by the sub-sub plots, and the N rates by sub-sub-sub plots (2.25×6.3 m plot size). The site alternated each year between two adjacent blocks following the cereal/legume or safflower (*Carthamus tinctorius*) rotation system practised at Tel Hadya. Thus, in years 1 and 2, the trial followed chickpea (*Cicer arietinum* L.) and safflower in years 3 and 4.

A trickle-irrigation system was designed and installed to provide a uniform soil moisture pattern within each SI treatment. Pressure-compensating emitters, with an approximate discharge rate of 2 l h^{-1}, were installed along polyethylene lines of 20 mm diameter. The spacing between laterals was 70 cm and between emitters 17.5, 35.0, and

Table 1
Mean monthly values of maximum and minimum temperature, Class A evaporation, and rainfall at Tel Hadya in northern Syria, 1992–1996[a]

Month	T_{max} (°C)	T_{min} (°C)	E_p (mm)	Rainfall (mm)	T_{max} (°C)	T_{min} (°C)	E_P (mm)	Rainfall (mm)
	1992/1993				1993/1994			
October	30.7	11.5	208	0	30.7	12.8	214	18
November	17.8	5.6	95	50	16.1	4.1	71	42
December	9.0	2.2	27	47	14.1	4.9	40	16
January	11.5	−0.3	48	51	13.3	3.7	37	109
February	11.8	0.1	61	45	13.8	2.8	64	137
March	16.8	2.4	105	40	18.9	4.0	101	12
April	24.0	7.3	182	2	26.9	8.3	197	11
May	27.0	11.4	218	45	31.6	11.8	298	13
June	34.4	15.3	377	1	34.7	17.7	432	0
$\sum$			1320	281			1453	358
	1994/1995				1995/1996			
October	30.3	14.8	187	12	28.3	10.5	193	9
November	17.8	7.5	75	109	17.2	4.6	66	59
December	9.6	1.6	38	45	12.4	2.0	36	31
January	12.2	3.7	35	41	11.2	3.3	39	74
February	16.5	2.7	56	18	14.4	4.3	59	47
March	18.9	3.4	98	33	15.8	6.6	66	143
April	23.1	6.9	158	44	20.6	6.7	117	27
May	31.6	11.5	275	27	32.2	12.3	278	5
June	35.7	18.6	406	1	35.6	17.6	385	0
$\sum$			1328	330			1239	395

[a] T_{max} = maximum temperature; T_{min} = minimum temperature; E_p = Class-A pan evapotranspiration.

52.5 cm, corresponding to the irrigated treatments full SI, 2/3 and 1/3 SI, respectively. The system of irrigation used in this study would not be economical for wheat at the farmer's land, but because of difficulties in obtaining good data with sprinklers (the area is windy), this system was used as a research tool to apply water accurately and evenly. Various emitter and lateral spacing together with a range of irrigation scheduling options were examined prior to this experiment to select the design parameters that achieve a uniform distribution of water similar to that of a sprinkler system (Oweis, 1992).

The source of the irrigation water was good-quality groundwater (EC 0.62 dS m^{-1}, SAR, 1.1). The cation concentrations were Ca^{++}, 3.4; Mg^{++}, 1.7; Na^{+}, 1.7; and K^{+}, 0.06 meq l^{-1}. The corresponding anions were: CO_3^{--}, trace; HCO_3^{-}, 2.6; SO_4^{--}, 1.7; and NO_3^{-}, 1.32 meq l^{-1}. The crop was planted in 17.5 cm rows at a rate of approximately 300 seeds m^{-2}, with N applied half at sowing and half top-dressed at the early tillering stage. As P was not a variable, a blanket application of 30 kg P ha^{-1} was applied to all plots prior to sowing.

Soil moisture was measured weekly, before and after each water application, and after each rain, using neutron probes. Access tubes were inserted in each of the sub-sub-sub plots of one replicate up to 1.8 m depth (depending on soil depth) for one variety (Omrabi 5). Water was applied to all treatments of the same date of sowing at the same time, i.e. when the root zone of the full SI treatment with 100 kg N ha^{-1} had lost 50% of its available moisture (1/2 the difference between field capacity and wilting point). The amount of water, which was then given, was calculated to restore root-zone moisture to near field capacity. The other

Table 2
Amount of irrigation water, application dates, and emergence dates for durum wheat sown at different times in the full supplemental irrigation (SI) treatment

Season	Sowing date[a]	Emergence date	Irrigation amount (mm)[b] and date	Total
1992/1993	10 November 1992	9 December 1992	133 (2/4); 146 (15/4); 118 (23/4);151 (21/5)	548
	10 December 1992	16 January 1993	95 (1/4); 100 (23/4); 100 (4/5); 146 (21/5)	441
	16 January 1993	20 February 1993	62 (6/4); 84 (23/4); 130 (22/5)	276
1993/1994	5 November 1993	22 November 1993	113 (6/4); 85 (21/4); 125 (16/5)	323
	5 December 1993	20 December 1993	106 (7/4); 84 (21/4); 164 (15/5)	354
	12 January 1994	28 January 1994	80 (5/4); 89 (22/4); 150 (16/5)	319
1994/1995	8 November 1994	23 November 1994	50 (9/3); 65 (27/3); 145 (14/4); 94 (6/5)	354
	10 December 1994	30 December 1994	63 (27/3); 97 (15/4); 94 (6/5)	254
	15 January 1995	6 February 1995	42 (29/3); 122 (15/4); 104 (5/5)	268
1995/1996	5 November 1995	17 November 1995	100 (5/5); 80 (14/5)	180
	12 December 1995	3 January 1996	100 (6/5); 100 (14/5)	200
	28 January 1996	17 February 1996	100 (7/5); 120 (14/5); 100 (26/5)	320

[a] The dates represent early, normal, and late sowing times.
[b] Gross amount of SI water (mm) applied to the full SI treatment; the other irrigation rates were 2/3 and 1/3 of the amount applied to full SI (application dates in parentheses).

treatments automatically received fixed proportions (1/3 and 2/3) of that amount. The root zone depth was estimated before each irrigation based on the depletion pattern of the soil profile. The amounts of irrigation water and application dates are given in Table 2.

During the growing season, measurements included: date of emergence (Table 2), plant and head numbers per m^2, and green leaf area and biomass at stem elongation, heading and anthesis. However, only grain and straw yields, grain protein, and vitreousness are reported here. The yield and harvest index were sampled in 7.9 and 0.3 m^2, respectively. Grain protein was calculated by multiplying the % N values from the Kjeldahl digestion by 5.7 (AACC, 1983), whereas virtuousness was visually assessed based on the presence of opaque blotches or 'yellow berry' in the grain. Analysis of variance was used to assess statistical significance using BLOCK STRUCTURE, TREATMENT STRUCTURE and ANOVA commands set in GENSTAT 5 program. Production functions and their corresponding predicted response surfaces were developed using variety, rate of N, rate of SI, and date of sowing, and their interactions, which were seen to account for the high variability. Further, the model was kept simple by ignoring interactions due to three factors or more.

3. Results

3.1. Grain and straw yields

All major factors, except variety, had significant effects on grain and straw yields. Overall rain-fed grain yield varied with the year (2.1–3.6 t ha^{-1}), with no consistent relationship with seasonal rainfall. Although there were differences between varieties, three of them (Cham 1, Cham 3, and Omrabi 5) were similar, giving slightly higher yields than Lahn. However, the overall effects of SI and N were dominant. With increasing water availability, from rain-fed to 1/3, 2/3, and full SI levels, the grain yields were 2.6, 3.8, 4.6 and 4.8 t ha^{-1}, respectively, whereas the straw yields were 4.9, 5.9, 6.7, and 7.2 t ha^{-1}, respectively. Nitrogen also had a consistent positive effect on yield. With the 0, 50, 100, and 150 kg ha^{-1} rates, the yields were 2.8, 3.9, 4.4, and 4.6 t ha^{-1}, respectively, with corresponding straw values of 4.3, 5.9, 6.9, and 7.5 t ha^{-1}.

The overall interaction between rainfall and irrigation water level with season, variety and sowing date are shown in Table 3 for grain and straw yield. Despite differences in rainfall, the response to SI was similar for the first 2 years; however, its effect decreased in subsequent years,

Table 3
Mean durum wheat grain and straw yields under rain-fed and varying levels of supplemental irrigation in relation to season, variety and sowing date[a]

Variable	Rain-fed		1/3		2/3		Full *SI*		Mean	
	Grain t ha^{-1}	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw
Season										
1992/1993	2.24	3.50	4.24	5.61	5.23	6.93	5.94	8.17	4.41	6.05
1993/1994	3.63	6.75	4.49	6.74	5.46	7.60	5.29	7.89	4.71	7.12
1994/1995	2.15	4.02	3.47	5.36	4.06	6.29	4.40	6.86	3.52	5.63
1995/1996	2.59	5.76	3.17	5.95	3.37	5.95	3.48	5.94	3.15	5.90
Variety										
Cham 1	2.65	4.91	3.91	6.11	4.51	6.67	4.91	7.26	4.00	6.24
Lahn	2.37	4.65	3.66	6.10	4.19	6.76	4.45	7.21	3.67	6.18
Cham 3	2.69	5.13	3.80	5.88	4.53	6.93	5.00	7.55	4.01	6.37
Omrabi 5	2.91	4.85	4.00	5.58	4.60	6.40	4.75	6.84	4.07	5.92
Sowing date										
November	2.72	5.32	4.26	6.96	4.76	7.61	4.98	7.86	4.18	6.94
December	2.75	4.98	3.69	5.56	4.34	6.30	4.65	6.86	3.85	5.93
January	2.49	4.35	3.57	5.23	4.27	6.17	4.71	6.92	3.76	5.67

[a] All interactions with irrigation are significant ($P \leq 0.001$), except for variety. Standard error of means for grain: water × year = 0.52; water × variety = 0.071; water × sowing date = 0.08.

possibly due to heat stress during the grain-filling period. Reflecting a significant interaction between water levels and sowing time, the responses to irrigation were highest with early sowing, with little difference between the later sowing dates. However, the pattern of response to SI levels was generally similar for the four varieties. As the responses for straw yields paralleled these of grain yield, only the latter data are subsequently presented.

The interactions involving applied N and the other management inputs are presented in Table 4. Again, a strong seasonal effect was evident. The data illustrate that the responses to N are related to yields of the unfertilized control and the factors that influence growth. On average, the addition of 50 kg N ha^{-1} increased grain yield by 1.1 t ha^{-1} compared to the control (2.8 vs. 3.9). The responses were positive but relatively lower for each additional 50 kg N, i.e. +0.5 t ha^{-1} for 100 kg N ha^{-1} and +0.2 t ha^{-1} for the 100 kg N ha^{-1} and 150 kg N levels. The responses to N were strongly modified by irrigation water levels. For rain-fed conditions, the response was limited to 50 kg N ha^{-1}. With limited SI (1/3), the response to N was maximum at 100 kg ha^{-1}, whereas at the two higher SI levels (2/3 and Full SI), responses continued up to 150 kg N ha^{-1}. In contrast to seasonal and water effects on N response, there was no effect of variety. Thus, the four varieties responded in the same way to added N. A delay in sowing date from November to December and January consistently reduced responses to N.

The significant parameters and significant interactions affecting the yield components of durum wheat were used in a regression model to develop the production functions of grain, total dry matter, and straw yields. The resulting general production function and regression coefficients for all the varieties and yield components are presented in Table 5. The interaction of variety with precipitation and with N was significant and accounted for a high percentage of variation to be included in the model. Examples of the resulted response surfaces that could be developed are depicted in Fig. 1 for the Cham 3 variety. These surfaces can provide the required information on production potential under any combination of factors involved.

Table 4
Mean effects of fertilizer nitrogen on durum wheat grain yield in relation to season, water levels, variety and sowing date[a]

Variable	N (kg ha − ¹)				
	0 t ha⁻¹	50	100	150	Mean
Season					
1992/1993	3.84	4.45	4.64	4.73	4.42
1993/1994	3.53	4.59	5.07	5.38	4.64
1994/1995	2.41	3.50	4.02	4.15	3.52
1995/1996	1.58	3.07	3.83	4.14	3.16
Water					
Rain-fed	2.21	2.77	2.89	2.76	2.64
1/3 *SI*	2.77	3.90	4.32	4.36	3.84
2/3	3.10	4.31	4.96	5.44	4.45
Full *SI*	3.28	4.63	5.37	5.83	4.78
Variety					
Cham1	2.90	4.02	4.44	4.62	4.00
Lahn	2.65	3.58	4.15	4.28	3.67
Cham3	3.89	3.97	4.49	4.69	4.01
Omrabi 5	2.91	4.04	4.50	4.80	4.06
Sowing date					
November	2.88	4.74	4.98	4.12	4.18
December	2.72	4.28	4.61	3.82	3.86
January	2.92	4.14	4.21	3.77	3.76

[a] All interactions with N are significant ($P \leq 0.001$), except for N × variety. Standard error of means N × water = 0.051; N × variety = 0.048; N × sowing date = 0.065.

Table 5
Estimates of regression coefficient for durum wheat production functions[a]

Variable	Grain	Straw	Total dry matter
Intercept (Cham1)	−0.995	−1.825	−1.63
Intercept (Lahn)	−0.720	−1.796	−2.00
Intercept (Cham3)	−0.980	−1.594	−1.45
Intercept (Omrabi5)	0.818	−2.354	−2.20
PR (Cham 1)	0.01123	0.01992	0.02863
PR (Lahn)	0.00910	0.01992	0.02863
PR (Cham3)	0.01115	0.01992	0.02863
PR (Omrabi5)	0.00566	0.01992	0.02863
N (Cham 1)	−0.00553	−0.01051	−0.0234
N (Lahn)	−0.00553	−0.01113	−0.0241
N (Cham 3)	−0.00553	−0.01112	−0.0235
N (Omrabi 5)	−0.00553	−0.00765	−0.0194
SI	0.03003	0.03359	0.05715
D	−0.2571	−0.2702	−0.5494
$PR \times SI$	−0.00007	−0.00009	−0.00015
$PR \times N$	0.000066	0.00011	0.00017
$PR \times D$	0.00078	0.00076	0.00158
$SI \times N$	0.000083	0.00009	0.0002
$N \times D$	−0.000067	−0.00013	0.0000
SI^2	−0.00001	0.00000	0.0000
N^2	−0.00007	−0.00009	−0.00012
D^2	0.00372	0.00408	0.00804

[a] *PR* = total annual precipitation (mm); *SI* = supplemental irrigation amount (mm); *N* = applied nitrogen (kg ha⁻¹) and *D* = delay in sowing after 1 November (days). Variance accounted for: grain 81.4%, dry matter 82.2%, and straw 80.1% $Y = a_0 + a_1(PR) + a_2(SI) + a_3(N) + a_4(D) + a_5(PR \times SI) + a_6(PR \times N) + a_7(PR \times D) + a_8(SI \times N) + a_9(N \times D) + a_{10}(SI_2) + a_{11}(N_2) + a_{12}(D_2)$, where Y is yield in (t ha^{-1}); a_0 is the intercept; a_1 to a_{12} are the regression coefficients of the independent variables and the significant interactions involved.

3.2. Grain and straw protein

The influence of all production and management factors on quality was just as pronounced as for yield. While grain protein levels varied with the season, some overall trends were evident. With increasing N levels, grain protein concentration rose from 9.6% with no added N to 11.7% with 150 kg N ha^{-1}. Similarly, delayed sowing, on average, increased protein from 9.9 to 11.3%, whereas the addition of irrigation water decreased protein from 11.7% under rain-fed conditions to 10% with 2/3 and full *SI*. The four varieties were generally similar in terms of protein content, ranging from 10.4 to 10.7%. The protein content in straw followed similar trends as in grain. For example, irrigation reduced straw protein from 2.8 to 1.8%, whereas 150 kg N ha^{-1} increased values from 1.7 to 2.6%, a substantial enhancement in terms of feeding quality.

As N has a dominant effect on cereal protein levels, the interaction of N and the other factors are presented (Table 6). The decrease in grain protein caused by irrigation was modified by the N application rate. However, the N required for maximum yield did not compensate for the reduction due to irrigation compared to rain-fed conditions, i.e. and 13.6 vs. 10.8% grain protein at the highest N level. Straw under fertilized rain-fed conditions contained almost twice the protein content compared to irrigated conditions with the same applied N level. While the interaction between N and varieties was significant, differences between varieties were minor; at the higher N

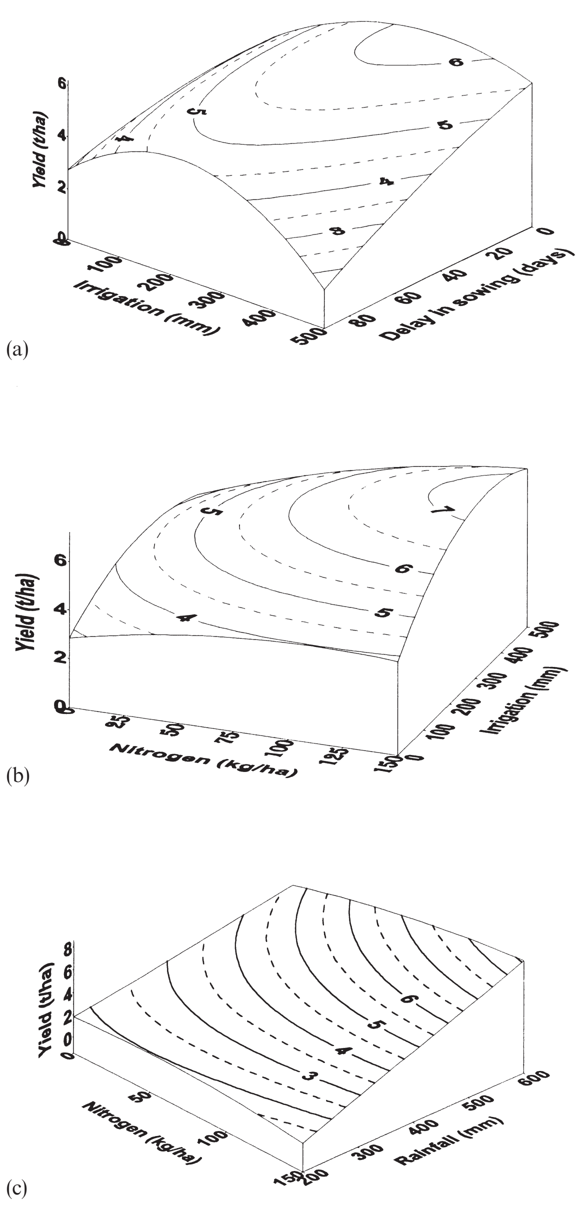

Fig. 1. Response surfaces of durum wheat (Cham 3) grain yield in relation to rainfall, supplemental irrigation, nitrogen and sowing date: (a) 100 kg N ha^{-1}, 350 mm rainfall and varying irrigation and sowing date; (b) early sowing, 350 mm rainfall and varying irrigation and nitrogen rates; (c) early sowing, no irrigation and varying rainfall and nitrogen rates.

rates, Omrabi 5 tended to have a lower grain and straw protein than the other three varieties. For all varieties, the increases in protein with delayed sowing date were accentuated by added N. Late sowing, relative to early sowing, increased the grain protein from 10.9 to 12.8% and straw protein from 2.4 to 2.9% at the highest N level.

3.3. Grain vitreousness

The variety and the other management factors (Table 7) significantly affected vitreousness. The overall mean percentage values were 67 (Cham 1), 72 (Lahn), 63 (Cham 3), and 52 (Omrabi 5). Rain-fed values were 79%, decreasing to 62% (1/3 SI) and 57% (2/3 SI), with no further decrease. Nitrogen consistently increased vitreousness (or reduced 'yellow berry') from 44 to 83%; the delay in sowing also increased vitreousness from 50 to 78%. Given the magnitude of these influences, it was not surprising that the interaction of N and the other factors were also significant.

The positive effect of N on percentage vitreousness varied with irrigation levels (Table 7). Under rain-fed conditions, N raised values as high as 92% from 57% under unfertilized conditions, whereas with irrigation, the maximum effect was 75%. Under any level of N, vitreousness varied for the varieties, with differences being most pronounced under unfertilized conditions; in all cases, Omrabi 5 had the lowest values. The interaction with sowing date and N was similarly variable; the differences were large (33–58%) under unfertilized conditions, but diminished as the N application rate increased.

3.4. Thousand-kernel weight

Though of lesser importance than either protein or vitreousness, the 1000-kernel weight (TKW) was also influenced by variety and the main factors, but the effects were less consistent and much smaller (Table 8). Overall, Cham 1 had the lowest TKW at 43 and Lahn the highest at 52. There were large differences between rain-fed (41) and irrigated conditions (47–49), with essentially no difference between irrigation levels. In marked contrast to other parameters, N had no effect on the mean TKW. However, the interactions between N and the other factors were significant. Added N tended to decrease the TKW values of rain-fed

Table 6
Nitrogen effects on grain and straw protein in durum wheat by irrigation level, variety and planting date[a]

Variable	Nitrogen ($kg\ ha^{-1}$)									
	0		50		100		150		Mean	
	Grain %	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain	Straw
Season										
1992/1993	10.6	2.0	11.6	2.3	12.8	2.6	13.6	3.2	12.1	2.5
1993/1994	9.6	1.5	9.7	1.6	10.2	1.8	11.0	2.1	10.1	1.8
1994/1995	9.0	1.5	9.5	1.8	10.4	2.2	11.1	2.8	10.0	2.1
1995/1996	9.3	1.8	9.0	1.6	9.8	1.9	11.2	2.3	9.3	1.9
Water										
Rain-fed	9.8	2.0	10.9	2.4	12.2	3.0	13.6	3.8	11.7	2.8
1/3 *SI*	9.3	1.6	9.7	1.7	10.4	2.0	11.6	2.5	10.3	1.9
2/3	0.5	1.6	9.6	1.6	10.1	1.8	10.9	2.2	10.0	1.8
Full *SI*	9.8	1.7	9.5	1.6	10.1	1.8	10.8	2.1	10.1	1.8
Variety										
Cham1	9.7	1.7	10.1	1.9	11.0	2.2	12.1	2.6	10.7	2.1
Lahn	9.6	1.8	10.1	1.9	10.8	2.3	11.8	2.9	10.5	2.2
Cham3	9.6	1.7	9.8	1.8	10.7	2.2	11.7	2.9	10.5	2.2
Omrabi 5	9.6	1.6	9.8	1.7	10.6	1.9	11.4	2.2	10.4	1.9
Sowing date										
November	9.3	1.6	9.5	1.7	10.1	2.0	10.9	2.4	10.0	1.9
December	9.5	1.7	9.7	1.8	10.5	2.1	11.5	2.5	10.3	2.0
January	10.1	1.8	10.6	2.0	‘11.7	2.3	12.8	2.9	11.3	2.3

[a] All interactions are significant ($P \leq 0.001$). Standard error of means, grain: N × water = 0.089; N × variety = 0.097; N × sowing date = 0.086. Standard error of means, straw: N × water = 0.051; N × variety = 0.052; N × sowing date = 0.049.

wheat, but slightly increased the TKW with irrigated conditions. However, the differences between varieties were fairly consistent with N application rates, with Lahn being highest in all cases. Added N had no effect on TKW with varying sowing dates.

4. Discussion

The most important implication from this study centers on the possible savings in irrigation water without causing any significant loss in potential yield. On average, applying 1/3 of full crop SI requirements (about 100 mm of irrigation water in an average year) achieved over 60% of the potential increase in yield with full SI. By applying 2/3 (about 200 mm) of the irrigation requirements, about 90% of the increase may be achieved. The increase in yield with 2/3 SI was, in all cases, within 3–15% of that achieved by full SI. Such yield increases clearly show the potential for water savings with proper conjunctive use of irrigation and rainfall in rain-fed agricultural systems. The strategy of applying restricted amounts of water based on the amount and distribution of rainfall in addition to the incremental effect of water on crop yield is the essence of the SI concept.

The mean rainfall WUE was about 1.1 kg grain and 3.2 kg of total dry matter per m^3 of rainwater. Although no significant differences were found between sowing dates, WUE ranged for N levels from 0.89, 1.06, 1.16 and 1.08 for 0, 50, 100, and 150 kg N ha^{-1}, respectively. The combined mean WUE of rainfall and SI water in producing grain yield was 1.15, 1.06 and 0.96 kg m^{-3} at the 1/3, 2/3 and full SI levels, respectively. However, when separating the contribution of irrigation water to increased crop yield, the mean WUE of SI water alone was 1.56, to 1.5, and 0.81 kg m^{-3} at 1/3, 2/3

Table 7
Vitreousness in durum wheat grain as influenced by nitrogen application in relation to season, irrigation level, variety and sowing date[a]

Variable	Nitrogen ($kg ha^{-1}$)				
	0 %	150	100	150	Mean
Season					
1992/1993	65.8	80.0	90.0	94.4	82.5
1993/1994	35.5	50.7	67.5	81.3	58.8
1994/1995	42.5	62.5	76.0	86.7	67.2
1995/1996	31.3	34.8	50.3	67.9	46.1
Water					
Rain-fed	57.2	78.7	87.9	92.1	79.0
1/3 *SI*	36.5	55.1	72.1	85.2	62.2
2/3 *SI*	38.9	47.5	62.8	77.9	56.8
Full *SI*	43.5	46.6	60.1	74.9	56.5
Variety					
Cham1	49.6	59.3	74.7	85.3	67.3
Lahn	51.4	67.6	80.5	87.6	71.8
Cham3	45.6	56.4	58.9	81.2	63.1
Omrabi 5	29.5	44.6	59.5	76.1	52.4
Sowing dates					
November	32.8	39.6	56.1	72.2	50.2
December	41.8	56.7	69.7	82.5	62.7
January	57.5	74.6	86.9	92.9	78.0

[a] All interactions with N are significant ($P \leq 0.001$), except for N × water. Standard error of means N × water = 1.41; N × variety = 1.65; N × sowing date = 1.47.

Table 8
Thousand-kernel-weight of durum wheat grain as influenced by nitrogen application in relation to season, irrigation level, variety and sowing date[a]

Variable	Nitrogen ($kg ha^{-1}$)				
	0 %	50	100	150	Mean
Season					
1992/1993	47.3	47.4	46.7	45.3	46.7
1993/1994	48.5	49.9	49.2	48.8	49.1
1994/1995	48.6	49.7	49.4	48.9	49.2
1995/1996	41.8	44.1	43.6	41.9	42.9
Water					
Rain-fed	42.7	42.4	41.1	39.6	41.5
1/3 *SI*	46.8	48.3	48.1	46.5	47.4
2/3 *SI*	48.7	50.3	49.8	48.9	49.4
Full *SI*	47.8	50.1	49.9	49.7	49.4
Variety					
Cham1	43.7	44.3	43.4	42.4	43.5
Lahn	51.2	53.2	52.7	51.9	52.3
Cham3	46.7	47.6	47.1	45.6	46.8
Omrabi 5	44.4	45.9	45.6	44.9	45.2
Sowing date					
November	46.8	48.5	47.8	46.2	47.3
December	48.1	49.6	49.3	48.6	48.9
January	44.7	45.3	44.6	43.8	44.6

[a] All interactions with N are significant ($P \leq 0.001$), except for N × water. Standard error of means N × water = 1.41; N × variety = 1.65; N × sowing date = 1.47.

and full SI levels, respectively. A substantially higher WUE (up to 2.72 $kg m^{-3}$) was obtained at optimal SI, N and date of sowing. Thus, based on water availability, a relatively small amount of water could be applied at a few strategic times and achieve substantial increases in yield and in WUE. In contrast to a companion study of bread wheat varieties under SI (Oweis et al., 1998), there were no marked varietal differences for these durum wheat varieties. Thus, whether in fact the farmer would opt for 2/3 or more of the water given with full SI depends on water availability, irrigation costs, and grain price. In a 5 year farmer-managed SI demonstration in northern Syria, farmers obtained on average 75–85% (depending on annual rainfall amount and distribution) of the maximum yield by applying only 50% of the amount of water required for full SI (unpublished work by ICARDA). The saved water may contribute to increasing the area under supplemental irrigation and/or to the sustainability of the limited water resources in the area.

The other factors described here are significant for crop production when seen in the context of SI. The crop-yield increases with applied N are expected given the long-established relationship between N and soil moisture (Ramig and Rhoades, 1962). The data from this study suggest that under such deficit-irrigation conditions, the maximum N efficiency would be achieved by using 50–100 kg N ha^{-1} combined with 1/3 to 2/3 of full irrigation. The models in Fig. 1 show that, given any variables, the influence on yield can be predicted. Clearly, the maximum expression of these parameters is only possible when high-yield potential cultivars are used; the cultivars used here have such traits and also incorporate disease resistance in their genetic make-up as well.

The final management parameter considered, sowing date, is more difficult to control under rain-fed conditions, as it is dependent upon the onset of the precarious early-season rainfall. Where rainfall is poor, farmers have little option but to delay sowing until as late as January (Photiades and Hadjichristodoulou, 1984). However, where irrigation water is available, adequate germination and emergence can be ensured with a small, i.e. 30 mm, irrigation after sowing. In order to obtain the maximum return from irrigation water and fertilizer, the earliest possible sowing should be sought. However, there are scheduling and logistic considerations. In large fields, spreading the sowing time between November to January would allow different portions of the field to have the peak water requirements at different times, although at a much narrower interval, it would reduce the size and the discharge of the irrigation system and, consequently, the overall costs of SI. The possible reduction in yield that may be caused by delaying sowing may be easily overcome by better economics.

Of the many quality traits commonly measured on durum wheat grain, protein content and vitreousness (or the absence of 'yellow berry'), are mainly influenced by management (Nachit et al., 1992). Thus, grain protein can be enhanced by the amount and manner in which N is applied (Bulman and Smith, 1993; Webster and Jackson, 1993) and, although irrigation decreases protein (Nachit et al., 1992), it can be increased by delayed sowing (Anderson, 1985) — all reflecting a dilution effect of N in the grain yield. These trends were shown in this study, the most significant being that irrigation alone decreased protein content while increasing yield, and the depression was compensated for by additional N over yield requirements. Thus, adequate N fertilization was needed to ensure durum wheat grain of an acceptable protein content, i.e. above 12%. While not perceived as being as important as grain protein, the enhancement of straw protein is of special significance in Syria, and the WANA region in general, as animals depend largely on stubble grazing.

For grain vitreousness, increasing N levels had a major effect in combating against the negative effect of irrigation. Similarly, Ryan et al. (1997b) found that an increase in N application, from 0 to 90 kg ha^{-1} reduced the incidence of 'yellow berry' from 31.9 to 9.5%, thus increasing grain vitreousness. Mahdi et al. (1996) has recently shown how environmentally sensitive this quality trait is, being dominant in one year and completely absent in the next. The genetics × environment interaction analysis of durum wheat of Nachit et al. (1992), which indicated that TKW was more genetically controlled, was borne out in this study. Allowing for the fact that the optimum date of sowing is well known to farmers, and whether they adhere to it is dependent on their circumstances, the only feasible strategy for improving durum wheat yields of acceptable quality is the judicial use of SI and N, the latter being able to counteract the protein-diluting effects of the former. This study highlights the incompatibility that may exist between quantity and quality and the need for a greater collaboration between breeders, agronomists and cereal technologists.

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