Influence of Supplemental Irrigation and Applied Nitrogen on Wheat Water Productivity and Yields

Aliasghar Montazar (Corresponding author)
Department of Irrigation and Drainage Engineering, Campus of Abouraihan
University of Tehran, P.O. Box 33955-159, Pakdasht, Iran
Tel: 98-292-304-0906 E-mail: almonta@ut.ac.ir

Maliheh Mohseni
Department of Irrigation and Drainage Engineering, Campus of Abouraihan
University of Tehran, P.O. Box 33955-159, Pakdasht, Iran
Tel: 98-292-304-0906 E-mail: maliheh_mo@yahoo.com

The research is financed by the deputy of Research and Technology, University of Tehran, Iran, through the research contract 7305002-01-P.

Abstract

A field experiment was conducted for three growing seasons to study the effects of seasonal water use and applied N fertilizer on yield attributes and water productivity indices of wheat in an arid region of Iran. The results revealed that yield attributes were significantly affected by irrigation and nitrogen treatments and growing season, and their interactions. Crop height, maximum leaf area index and biological yields were increasingly affected by the available water and N fertilizer. The findings indicated that the grain yield response to N was associated with water application levels. The water productivity indices were influenced by irrigation strategies and deficit irrigation effectively boosted productivity of irrigation water (W_I). The highest W_I was obtained at a seasonal irrigation water of 156 mm for different levels of applied nitrogen. For levels of applied N_1 (application 70% of the required nitrogen), N_2 (required nitrogen), and N_3 (application 120% of the required nitrogen), W_I ranged between 0.93 and 2.28, 1.30 and 2.75, and 0.98 and 2.47 kg m^{-3}, respectively. The data generated here suggest that under deficit irrigation, maximum water productivity (W_{ET}) would be achieved when 98 kg N ha^{-1} is combined with a 156 mm of supplemental irrigation. In this seasonal water use, W_{ET} value may be increased to 30% with N appropriate practice (practice N_2). Consequently, when limited irrigation water is combined with N fertilizer appropriate management, wheat water productivity can be substantially and consistently increased in the region.

Keywords: Irrigation, Nitrogen, Arid region, Wheat, Water productivity, Yield

1. Introduction

Wheat (*Triticum aestivum* L.) is the most important crop in Iran grown on 6.5 million ha of the total national cultivated land; irrigated wheat farms accounting for 35% of the total wheat lands. It grows mainly during dry seasons, where irrigation is necessary because precipitation in the growing season is far less than the crop water requirement. However, water resources are usually limited. Hence, irrigation scheduling is used to allocate irrigation water rationally in crop growing stages in order to maximize crop yield, water productivity and profit under the limited conditions.

Water–nitrogen relationships or production functions are considered as useful tools in the management of water and nitrogen application for optimization of crop productivity. These functions can be used in managing water resource for achieving maximum returns with minimum amount of water application as irrigation (English and Raja, 1996). If pests and diseases are controlled, yield of any crop in a given environment mainly depends upon irrigation and fertilizer nitrogen (N) management. Both water and nitrogen are subjected to losses by many pathways if not managed properly. Therefore, there is a considerable interest in strategies that enhance nitrogen use efficiency and productive use of applied irrigation water leading to increased productivity. Experimental results are used to develop general fertilizer recommendations for the whole region although experiments are conducted on a smaller scale.

A large volume of research is available on interaction effects of irrigation and fertilizer N on wheat (Prihar et al., 1981; Eck, 1988) and empirical analysis for computing combinations of water and N for realizing different yield targets (Gajri et al., 1993). A field experiment was conducted by Kibe et al. (2006) to study nitrogen-water relationships in late cultivation of wheat crop with adequate and limited irrigation regimes. The results revealed an exponential increase in irrigation water and nitrogen led to increases in LAI, CGR (crop growth rate), RGR (relative growth rate), NAR (net assimilation rate), performance, and biomass growth. The highest biomass growth belonged to the 60-90 post-harvest days with an irrigation depth of 53 kg (ha mm)$^{-1}$ followed by 28 kg (ha mm)$^{-1}$ for the 0-60 and 90-120 post-harvest days.

Arora et al. (2007) analyzed wheat yield responses to water and N-application for optimizing crop productivity under water limitations in a semi-arid sub-tropical irrigated environment. The analysis showed that grain yield and water productivity response to irrigation were influenced by extractable water capacity of soil. Soil effects on grain yield were more pronounced under no irrigation regime, and the effect decreased with increase in irrigation. Post-sown irrigation was more effective under conditions of low initial soil water. Initial soil mineral-N status influenced the amount of fertilizer N for a given initial soil water and post-sown irrigation scenario. Sepaskhah et al. (2006) derived some equations for determination of water and nitrogen levels at variable seasonal rainfall leading to maximum crop yield or profit with controlled water conditions for winter wheat in a semi-arid region. They reported that when land is limiting, for a given crop production and cost function, the sum of optimum applied water and seasonal rainfall; and the sum of optimum applied nitrogen and soil residual nitrogen; may be constant and optimum applied water or nitrogen does not depend on each other. When water is limiting, the sum of optimum applied nitrogen and soil residual nitrogen is constant similar to that obtained when land is limiting. The optimum nitrogen application was mainly influenced by soil residual nitrogen, but not by the water or land limiting conditions.

Nitrogen plays a key role in plant nutrition. It is the mineral element required in the greatest quantity by cereal crop plant and it is the nutrient most often deficient. As a result of its critical roles and low supply, the management of nitrogen resources is an extremely important aspect of crop production (Novoa and Loomis, 1981). Nitrogen is currently the most widely used fertilizer nutrient and the demand for it is likely to grow in future (Godwin and Jones, 1991). While applying nitrogen (N) and phosphorus (P) fertilizers and other management practices can increase dry matter production and grain yield (Cooper and Gregory, 1987; Ludlow and Muchow, 1990), several studies indicated that these practices could also have negative yield effects in seasons when water is severely limiting (Cooper et al., 1987; Van den Boogaard et al., 1996; El Mejahed and Aouragh, 2005; Rusan et al., 2005). The unpredictability of rainfall makes it difficult to determine the level and timing of fertilizer needed to attain optimum yields, as it might result in over/or under-fertilization with N (Rusan et al., 2005).

Water deficit is an important constraint for wheat yield generation in the dry environments. However, nitrogen availability could limit yield in a more important way than poor water conditions. The objective of the present study was to evaluate the yield and water productivity indices response of winter wheat in an arid region to the combined effects of seasonal water use and applied N fertilizer. The results of this study can be helpful in policy planning regarding irrigation management for maximizing net financial returns from limited land and water resources.

2. Materials and methods

2.1 Experimental site

Field trials were conducted at the experimental field of Campus of Abouraihan, University of Tehran, which lies in the 20 km east of Tehran, an arid region in Iran. It is located at a latitude of 33°28´N, longitude of 50°58´E with an altitude of 1180 m above mean sea level. The annual mean air temperature is about 16.9 ^{o}C, with the mean maximum and minimum temperatures are 40.5 and -6.7 ^{o}C, occurring in the month of August and January, respectively. Mean annual precipitation is about 164 mm with more than 90% falling in the period from October to the next June. Winter wheat grows mainly in this period. Table 1 shows monthly precipitation (P), and maximum and minimum temperatures (T_{max} and T_{min}) for the three study seasons (2001/2002, 2002/2003, and 2007/2008) and the monthly averages for a longer term (1978–2007). The first growing season rainfall (84 mm) was below the long-term average of 139.3 mm. The total rainfall in the second and third seasons was above (186.3 mm) and below (47.4 mm) the long-term average, respectively. In order to investigate the conditions of the water regimes in the study area, 30-year (1978-2007) statistics of the meteorological stations in the region were used.

The soil at the experiment site was silt loam, with the bulk density of about 1.39g cm^{-3}. Soil characteristics referring to five genetic horizons selected from the soil survey are presented in Table 2. Soil pH ranged between 7.5 and 7.8, its sodium absorption rate (SAR) between 1.4 to 1.8, and its electric conductivity (EC_e) was from 1.6 to 2.2 ds m^{-1}.

In the study area, the seedling stage was completed at the end of November. December, January, and February were the long winter season. In March, winter wheat began to turn green. The jointing stage was after the beginning of April. The booting stage generally started from the middle of April and the flowering stage at the end of April and beginning of May. Grain filling followed the end of the flowering stage and ends at the beginning of June.

2.2 Treatments

In this study, field trials were conducted in during three irrigation seasons (2001/2002, 2002/2003, and 2007/2008). One winter wheat cultivar, *Pishtaz*, widely adopted by farmers in the study area, was used. The bread wheat cultivar, adapted to the arid and semi-arid environments was planted on 5 to 10 November at a rate of 200 kg seeds/ha.

Wheat seeds were sown manually in rows 20 cm apart. Each elementary plot was 5m × 4m, and was separated from adjacent plots within the replicates by 50 cm in addition to 30 cm bund. The outer two rows were not harvested to eliminate border/edge effects. Thus, the effective width of separation between neighboring plots was 120 cm. The replicates were separated from each other by 160 cm blank space. The source of the irrigation water was groundwater with a good quality (pH: 7.6; EC: 1.1 dS m^{-1}; SAR: 1.3).

The experimental design was a randomized complete block (RCB) with four replicates. There were four levels of applied water and three levels of N application as treatments in the proposed plots. The applied water treatments included equivalent irrigation depth of winter wheat water demand (TW3), and three levels of providing 60% (TW1), 80% (TW2), and 120% (TW4) of water demand depth (TW3). Details regarding the amount of applied water and the application dates for each season are presented in Table 3.

The N treatments were equivalent nitrogen demand (TN_2), and two levels of providing 70% (TN_1), and 120% (TN_3) of nitrogen demand (TN_2) with respect to soil type. The recommended N dose in this area is 140 kg ha^{-1}. Fertilizer N as urea was applied at 50 kg ha^{-1} at around three months after sowing (middle of March), 50 kg ha^{-1} at tillering and 40 kg ha^{-1} at booting stages (for TN_2 treatment). Regards to the level of N application, fertilizer was applied for the other treatments in the similar dates of $TN_{1.}$ The soil residual mineralized nitrogen (NO3 and NH4) was considered as 66.2, 75.5, and 77.6 kg ha^{-1} for the three growing seasons, respectively. Also, harvesting was generally carried out around the beginning of June in study seasons.

2.3 Field evaluation procedures

Daily rainfall was measured by a rain gauge in a weather station located in the experimental station. All the meteorological data needed for the calculation of the soil water content, and potential evapotranspiration were derived from measurements of air temperature, relative humidity, wind speed, sunshine hour and solar radiation at the weather station located in center of the experimental field (2001/2002, and 2002/2003) and at distance of 1.0 km from the plots (2007/2008). Potential evapotranspiration was calculated by the Penman–Monteith approach. The actual crop evapotranspiration or seasonal water use (SET) was estimated by water balance equation as follows (Allen et al., 1998):

$$ET=P+I\pm\Delta\theta \quad (1)$$

where P (mm) is the precipitation, $\Delta\theta$ the change in water storage (mm) in the soil profile, and I the irrigation water applied (mm). Other components of soil water balance, such as capillary rising, deep percolation, and surface runoff were ignored (Ali et al., 2007).

Soil water content was measured gravimetrically in the depth range of 0–20 and 20-40 cm and with a TDR-probe (moisture point MP-917 with a 15 cm, two-rod, single-diode probe) from 40 to 100 cm depth at an interval of 20 cm on the before and one day after water application.

The leaf area index (LAI) values were measured on 50 m row length of crop at each plot with the help of a leaf area meter, and eight times per each growth season, using destructive sampling (Rockström and de Rouw, 1997). In order to investigate variations in crop height, ten samples were randomly selected from each plot to measure their heights using a measuring tape with an accuracy of 1 mm. Yield attributing data were collected from ten randomly selected plants from each plot. The crop was harvested manually.

Production functions were worked out by multiple regression analysis techniques, where the independent variables were the inputs: applied water, applied nitrogen, and year. The dependent variables were LAI, above ground biomass, grain yield and straw yield, height, and the yield attributes (1000 Kernel weight, Effective tillers/plant, Panicle length, Seeds per panicle). All the dependent variables were analyzed as a RCB analysis of variance technique using the SAS statistical package (SAS Institute, 2001). Differences among treatments were examined for statistical significance using the Least significant difference (LSD) test and Duncan's Multiple new Range Test (DMRT) criterion at 1 and 5% significance levels. Correlation coefficients of yield and components with yield were assessed using MSTATC program.

2.4 Water productivity indices

Water productivity (W_{ET}), and productivity of irrigation water (W_I), were calculated as follows:

$$W_{ET}=Y/ET \quad (2)$$

$$W_I=Y/I \quad (3)$$

where Y is the grain yield (kg/ha).

Technically, the marginal productivity of a particular resource is defined as the addition to the gross output caused by an addition of one unit of that resource while other inputs are held constant. Marginal productivity of irrigation water (MW_I) was calculated as:

$$MW_I=\Delta Y/\Delta I \quad (4)$$

3. Results

3.1 Seasonal water use

Table 4 shows the SET of the crop for the experimental seasons. The SET varied between 277.5 and 509.8 mm for treatments during the seasons. The highest SETs were recorded in treatments of TW_4N_1, TW_4N_2, and TW_4N_3 during 2007/2008 while the least SETs were recorded in treatments of TW_1N_1, TW_1N_2, and TW_1N_3 during 2001/2002. This was expected since treatments of TW_4 were regularly irrigated while treatments of TW_1 experienced limited water supply. Also, rainfall amounts during the wheat season were 79.5, 156.4 and 106.8 mm during 2001–2002, 2002–2003 and 2007–2008, respectively.

3.2 Wheat growth and yield attributes

The result of the statistical analysis of variance (ANOVA) is presented in Table 5. ANOVA shows that during the experimental seasons, there were significant effects due to the primary factors and their interactions. However, the effects were more consistently expressed for grain, straw, biomass, 1000 KW, plant height, effective tillers/plant (nos), panicle length (cm), seeds per panicle (nos). Differences due to year, applied water and nitrogen were highly significant for all variables, except applied water on seeds per panicle. In addition, the interaction of applied N with year were non significant on 1000KW, and plant height. Similarly, there were significant interactions between applied water with N and applied water with year for all variables, except plant height. There were significant interactions between applied water, applied N and year for all variables, except panicle length, and plant height.

Table 6 shows the correlation coefficients of yield attributes with grain yield. It was expressed for BY (r = 0.837), SY (r = 0.571), PH (r = 0.595), 1000KW (r = 0.198), EFT (r = 0.457), PL (r = 0.323), and SPP (r = 0.533).

One of the factors in guiding the photosynthetic efficiency of wheat is the leaf area, which definitely affect the growth and yield of crop. The leaf area index (LAI) at anthesis was assumed to be the maximum LAI attained by the crop. Maximum LAI for wheat is generally noticed at anthesis, a time that falls just after maximum growth rate of crop. Figure 1 shows the relationship of the leaf area index at anthesis (i.e. LAI_{max}) with water use (SET) and applied nitrogen. Lower levels of water use and applied nitrogen were seen to result in less leaf area, therefore, resulting in lower biological yield at lower levels of both factors (Figure 2). These corroborates the findings of Kibe et al. (2006) who stated that the sensitivity of expansive growth to water and nitrogen deficits is marked by reduction in leaf area. LAI_{max} reached its maximum value (4.22) at a seasonal water use of 509 mm and applied N of 140 kg ha^{-1}. In this level of applied water and nitrogen fertilizer, the biological yield reached to 18.53 t ha^{-1}.

Figure 3 presents the relationship of the crop height with the available water and applied N. Regarding the regression analysis, a quadratic relationship was observed between the crop height and the crop water use at each nitrogen level. Crop height was increasingly affected by the available water. Crop height reached its maximum value (545 mm) at a seasonal water use of 509 and applied N of 140 kg ha^{-1}.

3.3 Crop yield

Table 7 shows the mean grain and straw yields for the various treatments during the experimental seasons.

ANOVA showed that there was a statistical difference among the grain and straw yields of the different treatments at $P < 0.05$. A similar observation was reported by Tavakkoli and Oweis (2004) and Kibe et al. (2006). Also, there was not a statistical difference among the yields for each growing season. Treatments of TW_4N_2 and TW_4N_3 during 2002/2003 had the highest values of grain and straw yields, respectively. The seasonal water use of both treatments reached to 468.4 mm. Treatment TW_1N_3 during 2001/2002 recorded the least grain and straw yields, which its seasonal water use and applied nitrogen was 277.5 mm and 300 kg/ha, respectively. The reason for the lowest yield in TW_1N_3 can be attributed to the limited water supplies and high level of applied N. This treatment had a significant yield reduction compared to the control treatment (i.e. TW_3N_3) during the experimental seasons. The reduction in grain and straw yields was determined 243% and 136% across the seasons, respectively.

Water production functions, i.e. relationship between seasonal water use and grain were developed and presented in Figure 4. The functions were presented at the different applied nitrogen rates. Field-measured data for the three seasons were pooled to establish the relationships. The results show that increasing seasonal water use increased crop yields. For example, at 140 kg ha^{-1} fertilizer N, a grain yield of 2.45 t ha^{-1} was achieved in seasonal water use of 276 mm. For this N practice, grain yield was increased to 6.94 t ha^{-1} in seasonal water use of 509 mm. Such yield increase clearly supports the findings of Stewart and Musick (1982), Oweis et al. (1999) and Tavakkoli and Oweis (2004) in favor of the potential for conjunctive use of irrigation and rainfall in semi-arid regions.

It is an established fact that more the ET, more would be the growth and yield of the crop. The relationship of grain yield of wheat with seasonal water use could predict well in 49% to 68% of situations through quadratic fit. However, the quadratic relationship of the grain yield with seasonal evapotranspiration, with range of the variability indicates most of the deviations pertained to the lower productivity environments with water and/or nutrient stress and poor agronomic and protective management practices.

The results indicate that the response to N was associated with water application levels. As expected, the lowest response to N was under deficit irrigation, with no increase beyond the 98 kg ha^{-1}. As the N application rate increased, the effect on yield was limited by water use. The highest N level, tended to decrease yield at the low available water. Hence, under any soil water condition, a delay in crop emergence at autumn, on deficit irrigation, reduced the extent of yield response to added N.

4. Discussion

4.1 Influence of water and nitrogen on yield

The relationship between grain yields and seasonal water use at different applied nitrogen levels was shown in Figure 4. The production function, y(SET, N), was also obtained by multiple regression analysis as follows:

$$GY(SET,N)=-5.432*10^{-5}(SET)^2-1.206*10^{-5}(SET)+5.774*10^{-2}(N)^2+7.759*10^{-2}(N)-21.068 \quad (5)$$

With values for the coefficient of determination of R^2 of 0.736, standard error (S.E.) of 0.30, and number of sample n of 144, and where GY(SET, N) is the grain yield (kg ha^{-1}), SET is the seasonal water use (mm), and N is the applied plus soil residual nitrogen (kg ha^{-1}). The measured and estimated (from Eq. 5) wheat grain yields are compared in Figure 5. The trend and its correlation coefficient for the model under study were mentioned. The root mean square error (*RMSE*) was also calculated and presented. The evaluation reveals that the results obtained from the GY(SE, N) model are generally in good agreement with those obtained from experimental plots. Hence, the model enables us determine the cumulative degree of contribution of each factor i.e., water and nitrogen.

4.2 Influence of water and nitrogen on wheat productivity indices

The yield per unit of water consumed (W_{ET}), or irrigation depth (W_I), or marginal productivity of irrigation water (MW_I) are good indicators for assessing the performance of irrigation strategies (Ali et al., 2007). However, the high value of productivity indices in themselves are of little interest if they are not associated with high (or acceptable) yields, particularly in water scarce areas. Using the measurements of the study, the productivity indices (W_{ET}, W_I) were computed and presented in Figure 6. The W_I curve exhibits a negative correlation and the results indicate that a reduced water application increases the water productivity. This means that the water productivity indices were influenced by irrigation strategies and deficit irrigation effectively boosted productivity of irrigation water. The highest W_I was obtained at a seasonal irrigation water (SI) of 156 mm for all levels of applied nitrogen. For levels of applied N_1, N_2, and N_3, W_I ranged from 0.93, 1.30, and 0.98 kg m^{-3}, respectively, to 2.28, 2.75, and 2.47 kg m^{-3}, respectively. Also, the average W_I for applied N_1, N_2, and N_3 was 1.48, 1.83, and 1.65 kg m^{-3}, respectively. At some high level of yield, an incremental yield increase requires larger amounts of water. Consequently, W_I starts to decline as yield per unit land increases above certain levels. Similar results were reported by Zhang et al. (2004) and Ali et al. (2007). W_{ET} reached its maximum value (1.51, 1.98, and 1.72 kg m^{-3}) at a seasonal water application of 364, 416, and 416 mm for levels of applied N_1, N_2, and N_3, respectively. The average of this indice for applied N_1, N_2, and N_3 was 1.01, 1.40, and 1.32 kg m^{-3}, respectively. The most dramatic implication from this study is the saving in irrigation water with little loss in yield. The crop yield increases with applied N are expected, given the long established relationship between N and soil moisture (Ramig and Rhoades, 1962).

In arid and semi-arid regions where water is limited, small amounts of irrigation water can make up for the deficits in seasonal rain and produce satisfactory and sustainable yields. The findings of the research indicate that use efficiency for water and nitrogen was greatly increased by deficit irrigation. The data generated here suggest that under deficit irrigation, maximum W_{ET} would be achieved when 98 kg N ha^{-1} is combined with about 270 mm seasonal water use (114 mm, rainfall; and 156 mm, supplemental irrigation). In this seasonal water use, W_{ET} value may be increased to 30% with N appropriate practice (practice N_2). This may not be attained in the growing season when the adequate N practice is not occurred (practice N_1). Consequently, when limited supplemental irrigation is combined with N fertilizer appropriate management, wheat water productivity can be substantially and consistently increased in the arid and semi-arid regions.

Figure 7 shows MW_I values as a function of relative irrigation increase compared to 156 mm for applied N strategies. Trend line as a moving average format with two periods was also presented. The results show that the maximum marginal productivity of irrigation water is different for the applied nitrogen strategies. In the applied N_2, the variations rate of MW_I is larger than the others. On average, MW_I value increases until irrigation water increase of 50% of 156 mm (234 mm) and decreases after that for the applied N scenarios.

5. Conclusions

The findings illustrate that the wheat growth, yields and water productivity were strongly influenced by the climate variability and seasonal water use under nitrogen management. However, the yield is affected by the available water storage, as a result of the applied water and the available storage prior to irrigation, and the available nitrogen of the root zone. Globally, there were significant effects due to the both factors and their interactions on water productivity indices. The results show that use efficiency for water and nitrogen was greatly increased by deficit irrigation. On the other hand, water and N fertilizer applications should be limited due to scarce resources and environmental protection aspects. Hence, an analysis of crop yield production, water productivity indices, and profit maximization may be conducted to determine the optimal water and nitrogen allocation in arid and semi-arid regions. The analysis indicated that wheat water productivity may be substantially improved (2.75 kg m^{-3}) as a result of combining the limited supplemental irrigation strategies with N fertilizer appropriate management under climate conditions alike.

Acknowledgment

This study was funded by the deputy of Research and Technology, University of Tehran, Iran, through the research contract 7305002-01-P.

References

Ali, M. H., Hoque, M. R., Hassan, A. A., and Khair, A. (2007). Effects of deficit irrigation on yield, water productivity, and economic returns of wheat. *Agricultural Water Management*, 92, 151-161.

Allen, R.G., Pereira, L. S., Raes, D., and Smith, M. (1998). Crop evapotranspiration: guidelines for computing crop water requirements. *FAO Irrigation and Drainage Paper*, 56, FAO, Rome.

Arora, V. K., Singh, H., and Singh, B. (2007). Analyzing wheat productivity responses to climatic, irrigation and fertilizer-nitrogen regimes in a semi-arid sub-tropical environment using the CERES-Wheat model. *Agricultural Water Management*, 94, 22-30.

Cooper, P. J. M., and Gregory, P. J. (1987). Soil water management in the rainfed farming systems of the Mediterranean region. *Soil Use Management*, 3(2), 57–62.

Eck, H. V. (1988). Winter wheat response to nitrogen and irrigation. *Agronomy Journal*, 80, 902–908.

El Mejahed, K., and Aouragh, L. (2005). Green manure and n fertilizer in soil quality and profitability of wheat based system in semiarid morocco using nuclear techniques. In: *Management of Nutrients*, Water in Rainfed Arid, Semi-arid Areas for Increasing Crop, Production, IAEA-TECDOC-1468, pp. 89–106.

English, M., and Raja, S. N. (1996). Perspectives on deficit irrigation. *Agricultural Water Management*, 32 (1), 1–14.

Gajri, P. R., Prihar, S. S., and Arora, V. K. (1993). Interdependence of nitrogen and irrigation effects on growth and input use efficiency in wheat. *Field Crops Research*, 31, 71–86.

Godwin, D. C., and Jones, C. A. (1991). Nitrogen dynamics in soil plant systems. In: Hanks, J., Ritchie, J.T. (Eds.), Modeling Plant and Soil System. *Agronomy*, vol. 31. Madison, WI, USA, pp. 287–321.

Kibe, A. M., Singh, S., and Kalra, N. (2006). Water–nitrogen relationships for wheat growth and productivity in late sown conditions. *Agricultural Water Management*, 84, 221-228.

Ludlow, M. M., and Muchow, R. C. (1990). Acritical evaluation of traits for improving crop yields in water-limited environments. *Advance Agronomy*, 43, 107–153.

Novoa, R., and Loomis, R. S. (1981). Nitrogen and plant production. *Plant Soil*, 58, 177-204.

Oweis, T., Pala, M., and Ryan, J. (1999). Management alternatives for improved durum wheat production under supplemental irrigation in Syria. *European Journal Agronomy*, 11, 225–266.

Prihar, S. S., Sandhu, K. S., Singh, Y., and Singh, R. (1981). Effect of N rates on dryland wheat in relation to mulching previous crop or fallow. *Fertilizer Research*, 2, 211–219.

Ramig, R. E., and Rhoades, H. F. (1962). Inter-relationship of soil moisture level and nitrogen fertilization on winter wheat production. *Agronomy Journal*, 54, 123–127.

Rockström, J., and de Rouw, A. R. (1997). Water, nutrients and slope water, nutrients and slope position in on-farm pearl millet cultivation in the Sahel. *Plant Soil*, 195:311–327.

Rusan, M. M., Battikhi, A., and Zuraiqi, S. (2005). Enhancement of nitrogen and water use efficiency by optimizing the combination of soil, crop and nitrogen management. In: Management of Nutrients and Water in Rainfed Arid and Semi-arid Areas for Increasing Crop Production, IAEA-TECDOC-1468, 155–177.

SAS Institute. (2001). *The SAS System for Windows*, 8.02. SAS Institute, North Carolina.

Sepaskhah, A. R., Azizian, A., and Tavakoli, A. R. (2006). Optimal applied water and nitrogen for winter wheat under variable seasonal rainfall and planning scenarios for consequent crops in a semi-arid region. *Agricultural Water Management*, 84, 113-122.

Stewart, B. A., and Musick, J.R. (1982). Conjunctive use of rainfall and irrigation in semi-arid regions. *Advance Irrigation*, 1, 1–24.

Tavakkoli, A. R., and Oweis, T.Y. (2004). The role of supplemental irrigation and nitrogen in producing bread wheat in the highlands of Iran. *Agricultural Water Management*, 65, 225-236.

Van den Boogaard, R., Goubitz, S., Veneklaas, E. J., and Lambers, H. (1996). Carbon and nitrogen economy of four *Triticum aestivum* cultivars differing in relative growth rate and water use efficiency. *Plant Cell Environment*, 19, 998–1004.

Zhang, Y., Kendy, E., Yu, Q., Liu, C., Shen, Y., and Sun, H. (2004). Effect of soil water deficit on evapotranspiration, crop yield, and water use efficiency in the North China plain. *Agricultural Water Management*, 64, 107–122.

Table 1. Weather data for the three study seasons and a long period

Season	2001/2002				2002/2003				2007/2008				Long-term [a]			
	P (mm)	Tmax (°C)	Tmin (°C)	RH (%)	P (mm)	Tmax (°C)	Tmin (°C)	RH (%)	P (mm)	Tmax (°C)	Tmin (°C)	RH (%)	P (mm)	Tmax (°C)	Tmin (°C)	RH (%)
October	0	27.4	12.3	40.9	21.5	30.1	16.0	35.2	0.3	30.3	0	33.3	9.6	26.2	6.0	49.7
November	2	18.2	5.4	46.2	8	18.6	7.0	50.8	6.7	21.6	6.6	43.9	9.3	17.6	-1.8	59.1
December	0	13.6	3.3	64.0	25.5	9.0	0.4	63	0	11.2	1.1	69.0	15	11.9	-4.7	67.1
January	13	10.4	0.9	61.5	15	11.9	0.2	55.7	3.4	1	-9.0	71.2	19.6	10.2	-6.7	65.4
February	0	15.6	1.6	45.7	20.7	12.3	2.0	56.4	13.3	10.0	0.3	63.6	19.5	12.9	-5.4	58.2
March	15	20.7	6.5	38.1	41.5	16.4	4.5	48.9	0.1	23.5	9.2	33.2	32.6	16.3	-2.8	52.4
April	49	21.6	10.3	50.9	45.5	22.5	11.2	52.7	2.2	26.0	12.4	34.0	22.4	23.9	2.7	46.8
May	5	29.6	14.4	33.0	8.6	28.4	13.4	37.6	1.6	30.0	14.4	31.9	10.5	29.5	7.1	42.1
June	0	35.8	19.2	22.1	0	35.9	19.9	27.3	0	36.7	20.3	31.7	0.8	35.7	12.8	36.3

[a] Average parameters for long-term (1978–2007)

Table 2. Some physical properties of the soil used in the experiment

Genetic horizon (cm)	Layer thickness (cm)	Bulk density (g cm^{-3})	Porosity (%)	Field capacity (%)	Wilting point (%)	Sand (%)	Silt (%)	Clay (%)
0-25	25	1.39	43.2	28.3	11.5	20.2	74.7	5.1
25-35	10	1.42	41.4	25.8	11.1	34.2	60.6	5.2
35-57	22	1.32	46.7	29.4	12.5	36.2	58.5	5.3
57-82	25	1.41	42.5	21.9	11.2	27.2	65.2	7.6
82-100	18	1.27	50.2	33.4	14.2	26.2	66.5	7.3

Table 3. Totally applied water (mm) and application dates of each irrigation event during trials

Irrigation event	2001/2002					2002/2003					2007/2008				
	Date	TW_1	TW_2	TW_3	TW_4	Date	TW_1	TW_2	TW_3	TW_4	Date	TW_1	TW_2	TW_3	TW_4
1	25.11.01	36	48	60	72	28.11.02	25	35	42	53	03.12.08	34	44	56	67
2	18.03.02	30	40	50	60	27.03.03	25	32	40	50	24.03.08	32	43	54	65
3	04.04.02	30	40	50	60	18.04.03	25	32	40	50	14.04.08	32	43	54	65
4	21.04.02	30	40	50	60	29.04.03	25	35	44	51	30.04.08	32	43	54	65
5	05.05.02	36	48	60	72	09.05.03	26	35	46	52	10.05.08	33	46	57	68
6	16.05.02	36	48	60	72	16.05.03	30	39	48	56	18.05.08	38	51	61	72
Total applied water		198	264	330	396		156	208	260	312		201	269	336	402

Table 4. Seasonal water use of the crop for the experimental seasons

Treatment	Seasonal evapotranspiration (mm)		
	2007-2008	2002-2003	2001-2002
TW_1N_1	307.8	312.4	277.5
TW_1N_2	307.8	312.4	277.5
TW_1N_3	307.8	312.4	277.5
TW_2N_1	374.8	364.4	343.5
TW_2N_2	374.8	364.4	343.5
TW_2N_3	374.8	364.4	343.5
TW_3N_1	442.8	416.4	409.5
TW_3N_2	442.8	416.4	409.5
TW_3N_3	442.8	416.4	409.5
TW_4N_1	509.8	468.4	475.5
TW_4N_2	509.8	468.4	475.5
TW_4N_3	509.8	468.4	475.5

Table 5. Mean squares from analysis of variance for wheat growth indices and yield attributes

Source of variation	d.f.	1000 seed weight	Effective tillers/plant (EFT)	Panicle length (PL)	Seeds per panicle (SPP)	Plant height (PH)	Grain yield (GY)	Straw (SY)	Biological yield (BY)
Irrigation (I)	3	106.825 *	40.971**	1177.68**	19629.54 ^{NS}	173955.34**	71.752**	404.383*	261.859*
Nitrogen (N)	2	82.087**	13.742**	401.469**	6174.044**	28158.51**	37.234**	94.418**	47.541**
Year (Y)	2	22195.39**	340.705**	175304.54**	261261.62**	187625.25**	13.017 *	117879.72**	2463.57**
I×Y	6	76.172 *	5.225**	113.104*	4901.188**	774.975 ^{NS}	0.2218 *	84.832**	41.425**
N×Y	4	70.146 *	1.285*	110.914*	1547.47*	125.44 ^{NS}	0.1606*	61.097**	10.599**
I×N	6	106.83**	15.9**	184.84**	11980.18**	6955.61 ^{NS}	12.518**	63.399**	54.783**
I×N×Y	12	39.89**	1.33**	39.739 ^{NS}	2995.47**	30.987 ^{NS}	14.352 **	24.096**	6.506*

^{ns} Non significant

* Significant at the 5% level of probability

** Significant at the 1% level of probability

Table 6. Correlation coefficients of yield attributes with yield

	GY	SY	BY	PH	KW	EFT	PL	SPP
GY	1	0.571**	0.837**	0.595**	0.438 ns	0.457**	0.323*	0.533**
SY	0.571**	1	0.927**	0.618**	0.269 ns	0.384**	0.347*	0.458**
BY	0.837**	0.927**	1	0.683**	0.267 ns	0.464**	0.378**	0.547**
PH	0.595**	0.618**	0.683**	1	0.261 ns	0.188 ns	0.436**	0.347*
KW	0.438 ns	0.269 ns	0.267 ns	0.261 ns	1	0.290 ns	-0.002 ns	0.521**
EFT	0.457**	0.384**	0.464**	0.188 ns	0.290*	1	0.239 ns	0.819**
PL	0.323*	0.347**	0.378**	0.436**	-0.002 ns	0.239 ns	1	0.298*
SPP	0.533**	0.458**	0.547**	0.347*	0.521**	0.819**	0.298*	1

Table 7. Mean grain and straw yields for the various treatments

Treatment	Grain yield (t ha^{-1})				Straw yield (t ha^{-1})			
	2007-2008	2002-2003	2001-2002	Average	2007-2008	2002-2003	2001-2002	Average
TW_1N_1	2.96 DE	3.42 DE	2.69 DE	3.05	6.61 FG	7.71 FG	6.18 FG	6.83
TW_1N_2	3.55 CD	4.27 CDE	3.36 CDE	3.73	7.46 EF	8.51 EF	6.79 EF	7.59
TW_1N_3	2.08 E	2.4 E	1.96 E	2.15	5.01 G	5.85 G	4.56 G	5.14
TW_2N_1	3.7 CDE	4.27 CDE	3.53 CDE	3.83	8.36 CDEF	9.75 CDEF	7.49 DEF	8.53
TW_2N_2	4.73 BCD	5.46 BCD	4.47 BCD	4.89	8.55 CDEF	9.98 CDEF	7.7 CDEF	8.75
TW_2N_3	3.77 CDE	4.35 CDE	3.55 CDE	3.89	7.02 FG	8.19 FG	6.39 EFG	7.2
TW_3N_1	4.15 CD	4.79 BCD	3.9 CD	4.28	10.08 BCD	11.77 BCD	9.26 BCD	10.37
TW_3N_2	6.04 AB	6.97 AB	5.68 AB	6.23	9.31 CDE	10.86 CDE	8.36 CDE	9.51
TW_3N_3	7.15 A	8.25 A	6.8 A	7.4	11.97 AB	13.97 AB	10.68 AB	12.21
TW_4N_1	3.82 CDE	4.41 CDE	3.61 CDE	3.95	8 DEF	9.33 DEF	7.3 EF	8.21
TW_4N_2	6.79 A	7.83 A	6.34 A	6.98	10.49 BC	12.24 BC	9.51 BC	10.75
TW_4N_3	5.46 ABC	6.3 ABC	5.15 ABC	5.64	13.24 A	15.45 A	12 A	13.56

- Means were separated by Duncan's Multiple Range Test (DMRT)
- Treatments with the same letter in a column are not significantly different at $P < 0.05$

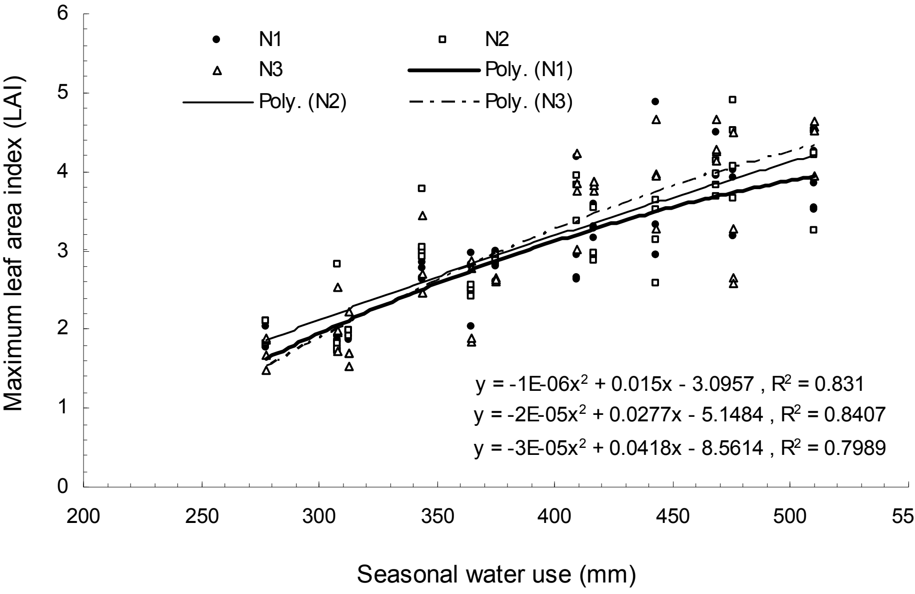


Figure 1. Relationship of maximum LAI with seasonal water use at different applied N rates

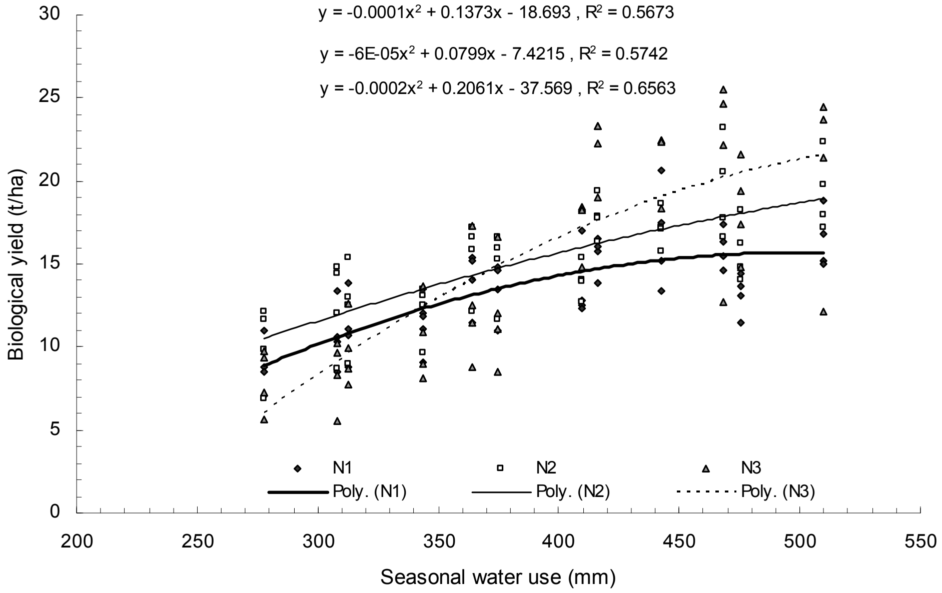


Figure 2. Relationship of biological yield with seasonal water use at different applied N rates

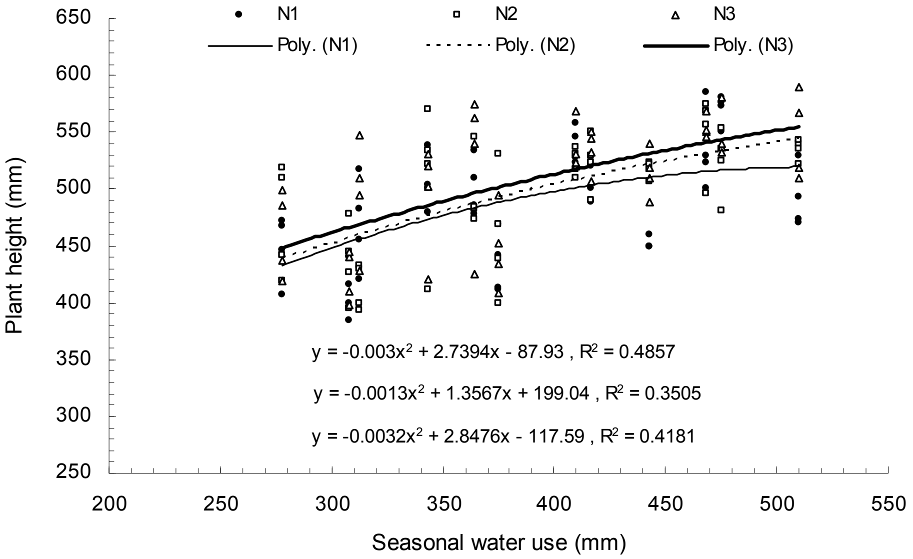


Figure 3. Relationship crop height with seasonal water use at different applied N rates

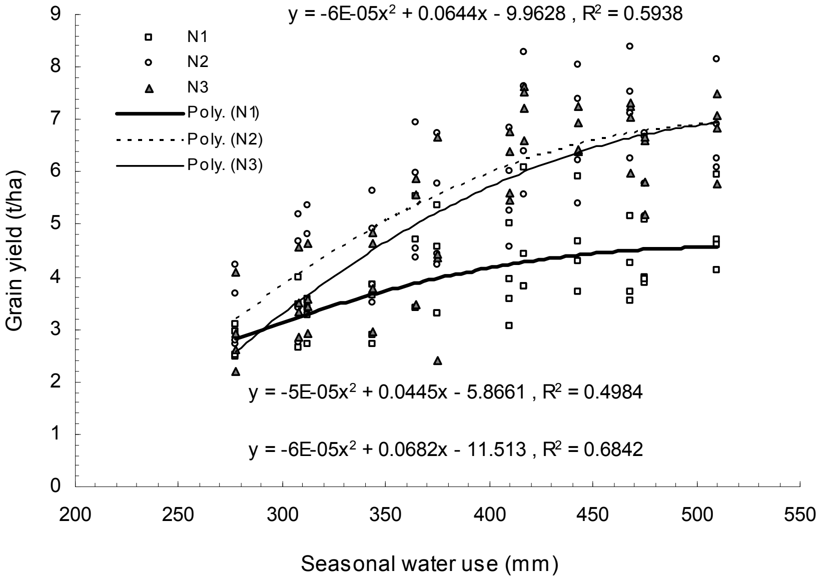


Figure 4. Water production functions at different nitrogen application rates

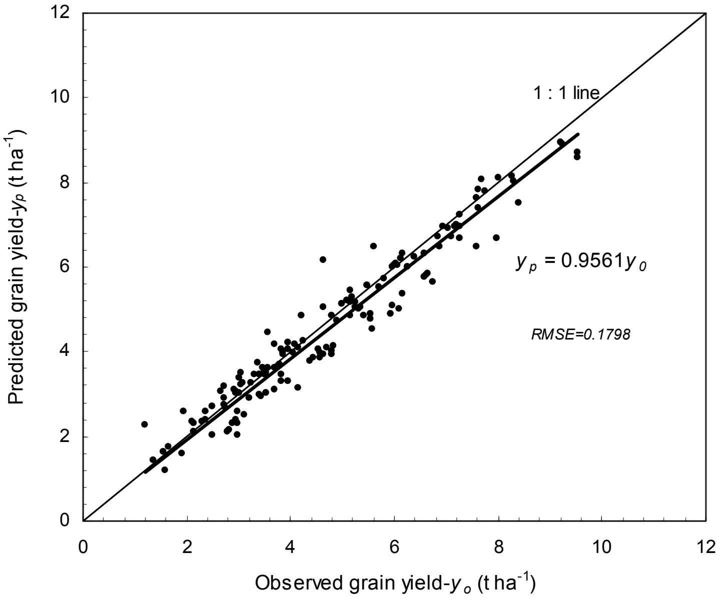
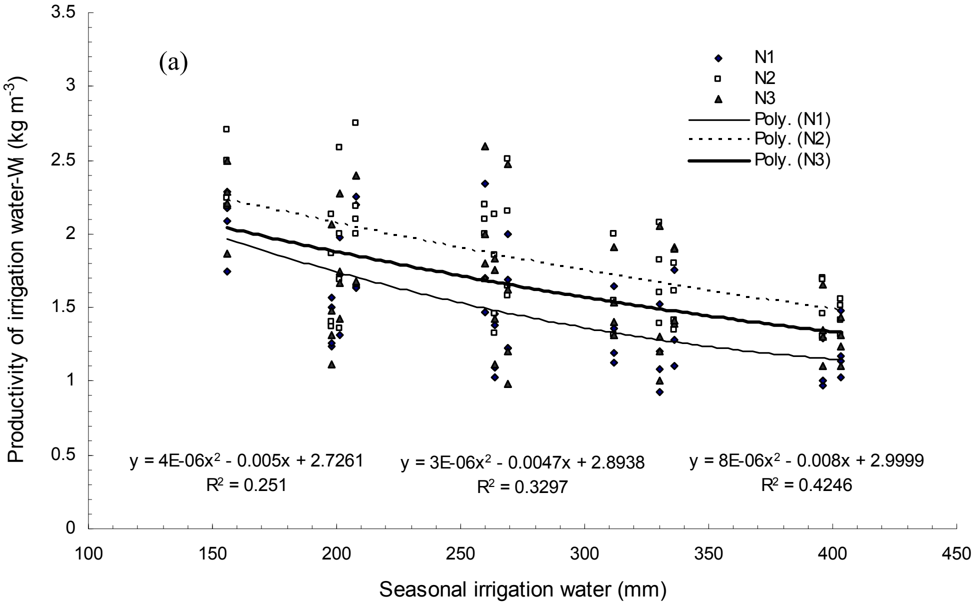


Figure 5. Comparison between observed and predicted grain yields



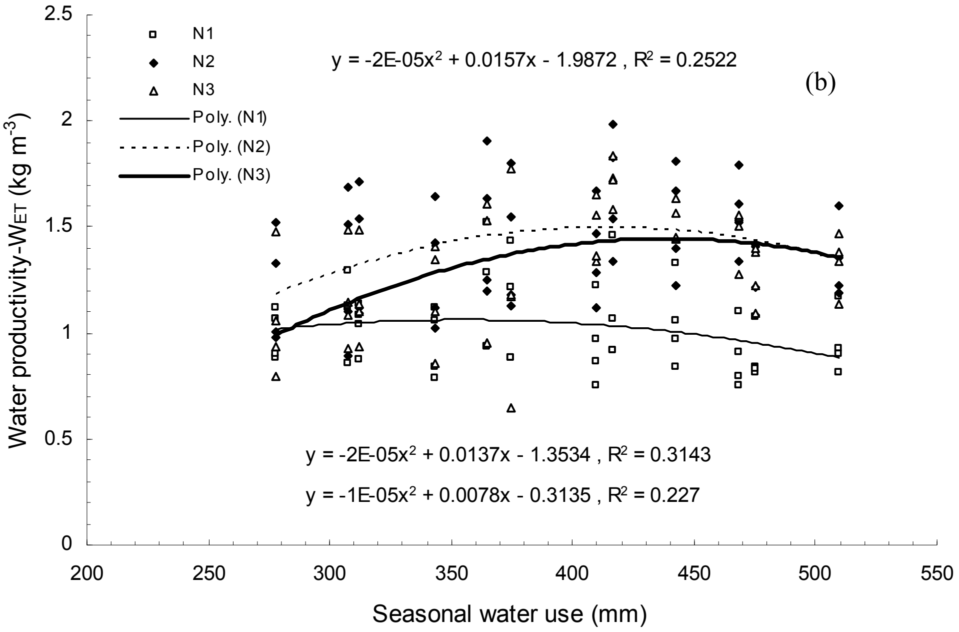


Figure 6. Productivity of irrigation water and water productivity as functions of (a) the SET, and (b) SI at different nitrogen application rates

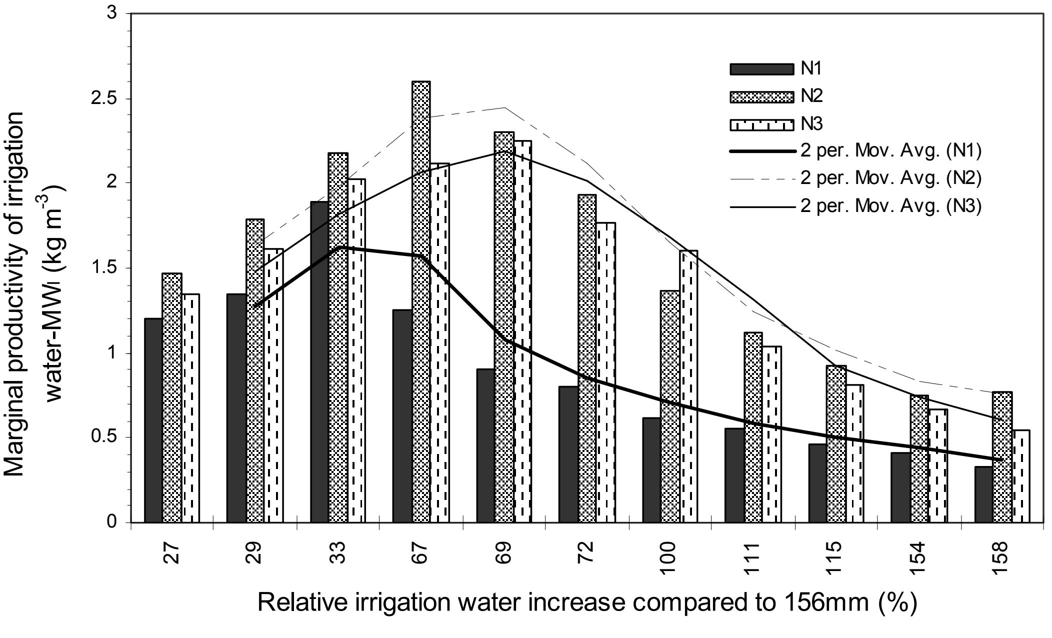


Figure 7. MW$_I$ indice as a function of relative irrigation increase compared to 156 mm