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Crop-yield/water-use production functions of potatoes (*Solanum tuberosum*, L.) grown under differential nitrogen and irrigation treatments in a hot, dry climate

T.C. Ferreira [a,*], *D.A. Gonçalves* [b]

[a] *Timoteo Caetano Ferreira, Head of Climatology Division, Universidade de Trás-os-Montes e Alto Douro (UTAD), 5001-911 Vila Real, Portugal*

[b] *Dionisio Afonso Gonçalves, President of the Polytechnic Institute of Bragança, Qta Sta Apolónia, 5300 Bragança, Portugal*

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ABSTRACT

During two consecutive years (1988–1989) field experiments were conducted in the region of Trás-os-Montes, N.E. Portugal. The work formed part of a wider research programme assessing the effects of water and nitrogen (N) on the productivity of potatoes in a hot, dry environment. Line-source experiments were carried out using potato crops (*Solanum tuberosum*, L.) subjected to four N levels (N_0, N_1, N_2 and N_3) and five irrigation (I) treatments (I_4–I_0). The main aims were to characterise crop productivity and develop the drought response factor K_y and the crop yield production functions in relation to rainfall and irrigation ($P + I$) and to total water-use (ET_c), that could be used to assess the benefits of irrigation and fertilisation practices in the region. ET_c was monitored by intensive field measurement of soil water content using a neutron probe device. Single values of total water applied ($P + I$) ranged from 148 to 387 mm in 1988 and from 295 to 724 mm in 1989. By contrast, single values of ET_c (including the contribution from soil water storage), ranged from 230 to 504 mm in 1988 and from 330 to 802 mm in 1989. Full irrigation increased mean yields of fresh tubers from 11.8 to 24.7 t/ha in 1988 and from 13.6 to 49.8 t/ha in 1989. Total fresh tuber yield from droughted crops tended to decline with increasing N fertiliser up to 80 kg/ha. Yield responses to $P + I$ (52–91 kg/(ha mm)) and to ET_c (62–105 kg/(ha mm)) varied with fertiliser application. In both years, the relative values of K_y were similar for all three fertilised crops (N_1, N_2 and N_3) regardless of nitrogen dosage. The mean K_y value in 1988 was 0.71 and 1.12 in 1989.

1. Introduction

Recent publications (FAO, 2004) have shown the importance of the potato (*Solanum tuberosum*, L.) as a global food crop, ranking fourth among other crops with an overall annual production of nearly 327 million tonnes and about 19 million ha planted. Since its introduction into Europe during the last quarter of the 16th century (Hawkes, 1992), it rapidly became the staple food of most people living on the continent. Portugal is no exception and the entire production of potatoes accounted for almost 6% of the Gross National Agricultural Product and in the N.E. region (Trás-os-Montes and Alto Douro) 22% of the Gross Agricultural Product (Martins, 1990). However, in a past report (Ferreira, 1996), comparison of potato yield values from Portugal for the 15-year period of 1979–1994, to corresponding values from other European Community countries, showed

* *Corresponding author*. Tel.: +351 259350281; fax: +351 259350480.
E-mail address: timfer52@gmail.com (T.C. Ferreira).
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Portugal ranking last with an average of 10 t/ha. Historical data from 1889 to 1941 compiled by Martins (1990) show a wide range of variation from as little as 5.4 up to 20.4 t/ha. Over the last decade, time trend technological improvement, especially in water and fertiliser management, has been responsible for an increase in potato yields in Portugal.

In the Trás-os-Montes and Alto Douro province of north-eastern Portugal (ca. 41–42°N and 7–8°W) the potato is also an important subsistence crop. However, locally, productivity is constrained on one hand by the severe soil water deficit which invariably develops during the hot dry climate that prevails during the summer season and on the other hand by the low water holding capacity and low organic matter content of the local soils. The soils around north-eastern Portugal have been cropped for years in a rotation system involving a cereal crop, potatoes and pasture and in the past, it was a common practice to fertilise these with animal manure (Moreira, 1984). However, with the advent of mineral fertilisation, farmers have been shifting from organic to mineral fertilisation with the consequent degradation of the soil's structure. Due to its complex topography and mountainous nature, winter rainfall in this region is much heavier than summer, resulting in frequent leaching of any residual fertiliser that may have been left in the soil from the previous crop. Rainfall during the summer (May–September) accounts for only 20–30% (150–250 mm) of the annual total, and the majority of crops experience severe water stress (Ferreira et al., 1996). Irrigation is therefore practiced to overcome this condition and to raise the productivity of crops, in particular of potatoes, which are sensitive to mild water deficits (Lynch et al., 1995; Wright and Stark, 1990). Due to the scarcity of water during summer season and the high-energy costs, this activity involves high financial risks to the grower, requiring before-hand knowledge of the likely benefit-to-cost ratio.

One practical way of assessing the financial benefits of irrigation in a given climatic environment and husbandry condition, is through the development of the relationship between tuber yield and water supply (Patel and Rajput, 2007). This approach allows field quantification of water-use efficiency for a given crop in a given environment and can be assessed by developing local crop-yield/water production functions of which the simplest is the yield responses to rainfall plus irrigation. Though the latter is an empirical approach, it also provides a simple means of judging the likely benefits of irrigation (Onder et al., 2005). The responses of potatoes described by such yield/irrigation water applied production functions developed in temperate climates (e.g., UK) showed values varying from 0.30 to 0.02 t/(ha mm) with an increase in irrigation application (Carr, 1983). These responses described by crop yield/water-use production functions are also commonly referred to as water-use efficiency (WUE) and the reported values for potatoes grown elsewhere in the world vary from 0.063–0.085 t/(ha mm) (Fabeiro et al., 2001) to 0.14 t/(ha mm) (Onder et al., 2005). Although this represents an improved means of assigning economic values to the total water-use, they bear a certain degree of uncertainty, shown by the two-fold variability, mainly due to the relative importance of soil evaporation and transpiration. Soil evaporation can represent up to 50% (Ferreira and Carr, 2002) of the total water used by potatoes in the climate conditions where this study is carried out. Therefore to allow for differences in actual rates of water-use and actual yield between sites and years, the use of yield response factors to drought (K_y) are recommended (Stewart et al., 1977). Values of K_y represent no more than a crop sensitivity factor to drought and they have been empirically derived by Stewart et al. (1977) and Doorenbos and Kassam (1986) for a range of crops including potatoes. However, the sensitivity of potato crop to drought in this region has not yet been determined, particularly under varying irrigation and nitrogen fertilisation. The knowledge of such a sensitivity factor can be of great use to help determine a managerial strategy for the optimum husbandry under a given local environmental condition.

The overall objective of the study was to examine the constraints to potato productivity imposed by the hot, dry climate prevailing in this region, particularly when cropping under varying levels of water and nitrogen fertiliser. Details of actual water use have been presented in a previous paper (Ferreira and Carr, 2002). Therefore, in this paper, an outline is given of crop-yield responses of potato crops to water applied and water-use and the corresponding crop yield response factors to drought, obtained under varying levels of irrigation and nitrogen fertilisation.

2. Methodology

2.1. *Site, experimental design and crop management*

Two trials were carried out during the summers of 1988 and 1989 in adjacent small (0.5 ha) fields, in north-east Portugal (latitude: 41°49′N; longitude: 6°46′W; altitude: 720 m) at Santa Apolónia Farm, Bragança Polytechnic. The experiments were carried out in previously fallow fields which were covered by grass for the previous three years, each with a total area of around 5000 m^2. In 1988, the soil at Site 1 (S1), characterised by a soil mass made of alluvial deposits, was classified as a Gleyi-Umbric Fluvial. In 1989 the soil at the adjacent Site 2 (S2), characterised by a good fertile mantle of loose material was classified as Eutric Regosol (FAO-UNESCO, 1988). The soils in both fields were described as silt-loams with organic matter content decreasing from 3% at the surface to 0.5% at depth of 1 m. Both fields showed total nitrogen content varying (1988–1989) from 0.16–0.20 (%) at the surface to 0.030–0.050 (%) at 1 m, with pH varying between 5.3 and 5.7 at both sites. Corresponding values of organic carbon content varied from 1.32 to 1.66 (%) at the surface to 0.30–0.50 (%) at depth of 1 m. These values are representative of a soil from regions where winter rainfall is heavier than summer rains (Brady, 1974) and are within those found by Martins (1987) for other sites in N.E. Portugal where potato is cropped. The soil water holding capacity varied between 150 mm/m on Site 1 (1988) and 200 mm/m on Site 2 (1989). There was no sign of the water table at 1.8 m depth.

Both experiments were based on the line-source design first described by Hanks et al. (1976) with four main nitrogen treatments (0 (N_0), 80 (N_1), 160 (N_2) and 240 (N_3) kg/ha) replicated four times, two on either side of a central pipe. There were five differential irrigation/drought treatments ranging from the fully irrigated (I_4) to un-irrigated, rainfall-only (I_0), with three partially irrigated treatments (I_1, I_2 and I_3), making a total of 20 treatment combinations.

In both experiments, pre-sprouted tubers (cv. Desirée, class AA1) were planted by hand, on 1 June 1988, and on 11 May 1989 to a density of about 45,000 plants/ha. Basal fertiliser applications of 330 kg/ha of phosphate (P_2O_5) and 270 kg/ha of potash (K_2O) were applied to both experimental fields according to results of soil laboratory analysis to ensure that these components would not represent additional limiting factors in the study. Nitrogen was applied as ammonium sulphate at variable rates (described above). Emergence (50%) occurred 34 days after planting (DAP) in 1988, and 26 DAP in 1989.

In 1988, rainfall during the growing season (May–September inclusive) totalled 248 mm. The spring was relatively wet with 104 mm of rain before planting and an additional 131 mm of rain fell just after planting. Therefore, it was not necessary to irrigate to ensure successful crop establishment. Mean maximum daily air temperatures varied from 17.1 (May) to 28.3 °C (August) and the total pan evaporation (E_{pan}) was 734 mm during the 5-month period. By contrast, the corresponding values of seasonal total rainfall and pan evaporation were 125 and 940 mm in 1989. Mean maximum daily air temperatures varied from 22.5 °C (May) to 32.1 °C (July). Because in 1989 the potential soil moisture deficit at the beginning of the season was high, a total of 122 mm of irrigation was applied to the crop (in four applications) in addition to 75 mm (42 mm in May and 33 mm in June) of rain to bring the soil profile to field capacity.

Further details of the site, climate and experimental design, crop management and calculation procedures are presented by Ferreira and Carr (2002).

2.2. *Irrigation application*

Water applied to each of the treatments during each irrigation event was equal to the amount of water lost as actual evapotranspiration (ET_a) over the period less effective rainfall. Therefore, due to cooler and wetter environmental conditions that prevailed prior to planting and during the first part of the growing season in 1988 when compared to 1989, there were only eight differential irrigation applications. These took place at approximately weekly intervals from 52 days after planting, DAP or 18 days after 50% emergence (DAE), until 20 days prior to harvest which took place 120–122 DAP. On the other hand, the larger climatic demand observed in 1989, with temperatures well above normal for the greater part of the season, necessitated more water applied in nine weekly differential applications beginning 56 DAP (31 DAE) and ending 30 days prior to harvest which occurred 142–143 DAP. Therefore, the total water applied through irrigation and rainfall during the whole season in selected irrigated treatments (fully irrigated I_4, partially irrigated I_2 and rainfed I_0) ranged between 370 and 387 mm (I_4); 220 and 240 mm (I_2), and 148 mm (I_0) in 1988 while in 1989 these values were: 630–724 mm (I_4); 470–520 mm (I_2) and 295–330 mm (I_0). The corresponding seasonal water-use (ET_c), that is, accounting for the depth of water taken from soil storage during the season was: 390–504 mm (I_4); 340–400 mm (I_2); 230–320 mm (I_0) in 1988; and 720–802 mm (I_4); 610–680 mm (I_2) and 330–420 mm (I_0) in 1989.

2.3. *Crop water-use and soil water content*

The cumulative evapotranspiration over the period of drought treatments (ET_c) was calculated by summing the weekly estimates of actual evapotranspiration (ET_a). The value of ET_a, between successive irrigation applications was estimated weekly using the following equation:

$$ET_a = (P + I) \pm \Delta S - D_r - R_o \quad (1)$$

where P is the rainfall and I is the irrigation water applied to individual treatments and both measured, ΔS is the change in soil water storage over the period concerned. ΔS was calculated between successive weekly irrigations for each of the soil layers and integrated over the whole soil profile, for each treatment combination, using a water balance equation:

$$\Delta S = \sum[(\theta_v - \theta_{v+1}) \times D] \quad (2)$$

where θ_v and θ_{v+1} are the volumetric soil water contents (%) before and after successive irrigations and D represents the incremental soil depth. During the drought periods, the soil water content was determined at incremental (0.2 m) soil depths from 0.1 to 1.1 m depth in all 16 nitrogen treatments plots and drought treatment sub-plots I_4, I_2, and I_0. Measurements were made using gravimetric sampling in the top 0.1 m layer of the soil and a neutron probe (Wallingford MK IIL, Didcot Instruments Company, Ltd., U.K.) at depths below this. Readings were taken before each irrigation and 24 h afterwards. The probe was calibrated in both years (1988: $n = 18$, $r^2 = 96\%$; 1989: $n = 16$, $r^2 = 96\%$; volumetric water content range 10–43%) separately for each site according to Bell (1976) and the Institute of Hydrology (1981). D_r is drainage occurring below the rooting zone (0–1.1 m). This was monitored by the change in the water content and soil matric potential gradients. Soil matric potential gradients, monitored at depth in the wettest plots with tensiometers (Irrometer, Soil Moisture Equipment Group, California), indicated that there was negligible deep drainage (D_r). R_o is run-off water which was minimized and assumed to be zero, as the rates of water application were controlled and always less than the initial infiltration capacity and close to the base infiltration rate of the soils. Any accidental excess water was prevented from running-off by micro-catchments dug between adjacent subplots.

2.4. *Tuber yields*

Total tuber fresh weight was obtained at final harvest when all crops were supposed to be ripe. However, in both years, at the time of harvest, the foliage of plants in the well-fertilised (N_3) and fully irrigated (I_4) treatment combinations was still green, whilst in the unfertilised (N_0) and the un-irrigated (I_0) plots the plants were in an advanced state of senescence. Final yield was then obtained from at least 50 plants from the centre of each of the sub-plots. These were removed from the soil with a fork to recover all the tubers, in a total of 4000 plants. The tubers were immediately placed in plastic bags, numbered and their fresh weights recorded, respectively.

2.5. Crop yield/water-applied and water-use production functions

For both years, crop-yield/water production functions were determined by linear regression of the fresh weight of the tubers (FW_{tub}) at the final harvest to the total depth of water applied ($P + I$; $n = 20$), and to total (seasonal) crop water-use (ET_c; $n = 12$). In addition, the relative yield response factor to drought (K_y) was determined by relating the relative yield decrease ($1 - Y_a/Y_{max}$) to the corresponding relative evapotranspiration deficit ($1 - ET_a/ET_{max}$) where Y_a and ET_a represent the actual yield and the corresponding total actual evapotranspiration from planting to harvest, for each nitrogen treatment, and Y_{max} and ET_{max} represent the maximum yield and the corresponding evapotranspiration total observed in the best yielding single treatment combination for each season (Doorenbos and Kassam, 1986; $n = 12$).

2.6. Statistical analysis

Because of differences in planting dates, soil type and season, data was submitted to analysis of variance per year separately. To allow for any systematic variation across the experimental area, such as a fertility gradient, covariance analysis, with distance of each sub-plot from the line-source as the co-variate, was used to test for treatment differences in fresh and dry tuber yields (Morgan and Carr, 1988). The relationships between yield components and water applied and water use were determined using linear regression analysis across nitrogen fertiliser treatments for each year. Comparison of treatment means was carried out using the least significant difference at $P < 0.05$.

3. Results

3.1. Climate

The total annual rainfall of the two experimental years does not explain the actual conditions observed during the respective growing seasons. The total annual rainfall amounted to 734 mm in 1988 and 982 mm in 1989. Though in both years the climate during the growing season was that of typical Mediterranean summer, 1988 was wetter and cooler than 1989.

In 1988 (Fig. 1a), rainfall occurring between planting and harvest (June–September) represented only 20% (144 mm) of the annual total with 85% of which falling during the first two months after planting (June and July). By contrast, rainfall from May to September in 1989 represented only 13% (125 mm) of the annual total and only 80% of the long-term average rainfall for the growing season. Contrary to 1988, the first part of the growing season in 1989 was dry with rainfall during May and June totalising only 75 mm.

In both years mean temperature (Fig. 1a) rose gradually from the beginning of the growing season (May) reaching a peak during July and then falling again towards the end. However, in 1989 mean temperature was well above that of 1988 mainly at the beginning of the season (May–July) reaching a maximum difference of about 5 °C during July. This was a reflection of the daily maximum temperatures that prevailed during July when for several days they were between 35 and 37 °C.

The end result of the above climatic features was the building up of a significant potential soil water deficit (Fig. 1b), as represented by the difference between rainfall (P in mm) and U.S. Weather Bureau (USWB) 'A' pan evaporation (E_{pan} in mm). Values of P-Epan were negative right from the start of the season in 1989 and amounted to about −820 mm by the end of the period. By contrast, in 1988 a slight potential soil water deficit only occurred by mid June and the total value accumulated by the end of the season though high (−500 mm), represented only 62% of that observed in 1989.

3.2. Soil water content

Variations with time in mean soil water content (θ_v, %volume) within the 1.1 m depth for different irrigation treatments show a similar pattern for both years (Fig. 2a and b). Prior to the start of drought treatments, rainfall and supplementary irrigation kept the mean soil water content of the plots at near field capacity (FC). Once the drought treatment was commenced, in both years, the irrigated plots exhibited cyclic fluctuations with each irrigation event as one would expect. Each irrigation

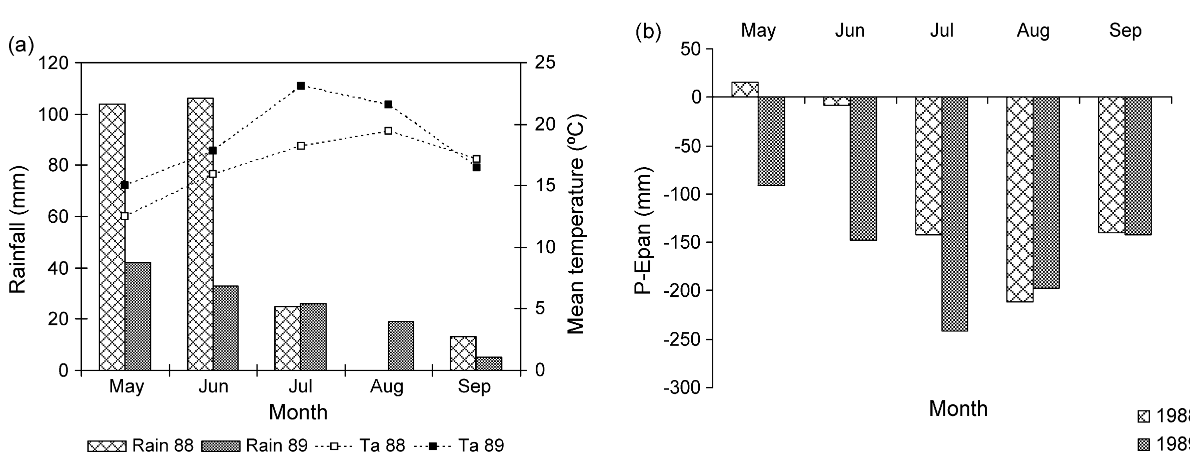

Fig. 1 – Time course of (a) monthly rainfall totals (mm) and mean monthly air temperature (°C); (b) monthly potential soil water deficit P-Epan (mm) during the growing season (May–September) in 1988 and 1989 in Bragança.

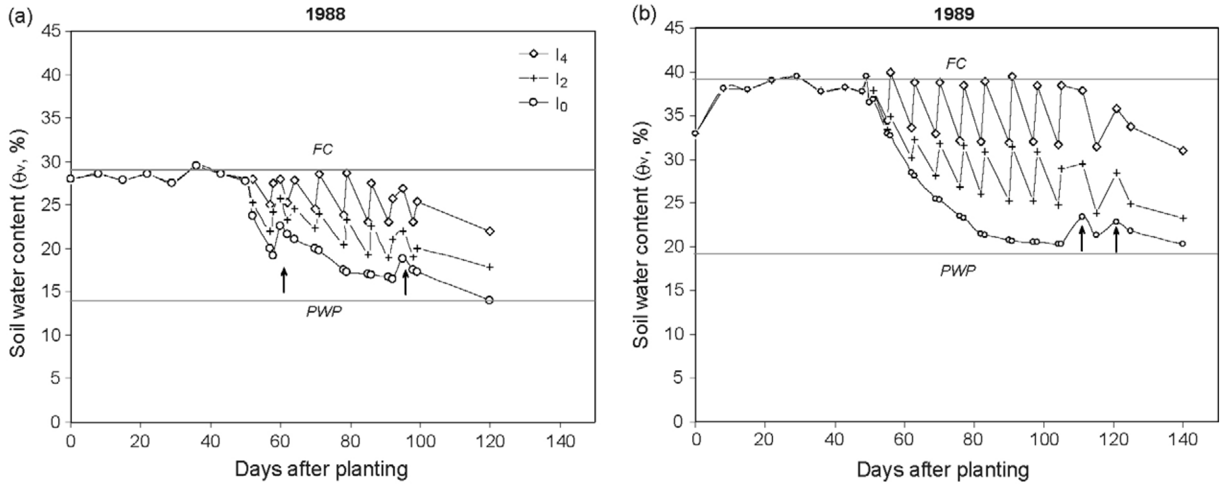

Fig. 2 – Variation in mean soil water content (θ_v, %) with time for fully irrigated (I_4), partially irrigated (I_2) and rain-fed (I_0) treatments in (a) 1988 and in (b) 1989 across all four nitrogen treatments (N_0–N_3). Values of total water applied refer to measurements made between planting and final harvest, 120 DAP in 1988 and 140 DAP in 1989. Upper line indicates the mean value of field capacity (FC) and lower line the mean permanent wilting point (PWP) of the soil. Black vertical arrows indicate rainfall event.

application had the desired effect of replenishing the soil profile with the expected rise in θ_v. After each weekly interval scheduled for irrigation, the soil had dried to increasingly lower θ_v values as the season progressed. At the end of a drying cycle, mean soil water content in fully irrigated plots (I_4) varied from 90% of the available water (AW) in the soil profile, at the beginning of the drought imposition to about 60% at the end of this period. By contrast, in the partially irrigated treatments (I_2) mean θ_v measured at the end of a given drying cycle gradually decreased as the season progressed, resulting in a consequent greater fall of soil water storage than those plots under fully irrigation. In both years, mean soil water content varied from 80% of the AW at the beginning of the drought imposition to about 30% AW at the end of the period. In the treatments supplied only with rain water (I_0), θ_v in both years varied steadily from near FC values at imposition of drought treatment to extremely low values at about 70–80 DAP, beyond which soil water content did not change greatly, being only disturbed by occasional rainfall events. By the end of the season mean values of θ_v reached near permanent wilting point (PWP), particularly in 1989 under warmer and drier environmental conditions. In both years, a distinct greater soil water deficit developed in these rain-fed treatments as compared to the irrigated treatments and considerably more water was being extracted from the soil profile. Soil water content of the rain-fed treatments decreased steadily with time, though somewhat faster in 1989, as a result of the warmer and dryer conditions and the larger growing season than 1988.

3.3. *Tuber yields*

In both years, irrigation had a clear effect on total tuber fresh weight with yields increasing steadily from rain-fed to fully irrigated conditions. In 1988, yields (total tuber fresh weight in t/ha) varied from 14.0 (N_0), 11.0 (N_1), 10.0 (N_2) 12.4 (N_3) in rain-fed plots to 28.9 (N_0), 23.3 (N_1), 22.2 (N_2) 24.4 (N_3) under the full irrigation regime (Fig. 3a).

The maximum yield obtained in 1988 averaged across nitrogen treatments when no irrigation was applied (I_0) was about 12 t/ha rising to about 25 t/ha in the well-irrigated plots (I_4). However, in 1989, the yields were substantially more ($P < 0.01$) from well-irrigated plots with about 50 t/ha, but only about 14 t/ha without irrigation. Nonetheless, they also showed similar variation among treatments ranging from 17.3 (N_0), 12.6 (N_1), 12.3 (N_2), 12.2 (N_3) when the crops received no additional water to 48.4 (N_0), 49.3 (N_1), 50.1 (N_2), 49.4 (N_3) under the maximum irrigation treatment (Fig. 3b).

Surprisingly, the responses to nitrogen were unexpected: in 1988, yields, regardless of irrigation treatment, tended to decline with increasing nitrogen application, at least up to 80 kg/ha (N_1), then remained relatively constant or oscillated as nitrogen levels increased further (Fig. 4a).

By contrast in 1989, the main significant ($P < 0.01$) feature of the negative effect of nitrogen fertiliser (N_1) was only observed in the un-irrigated (I_0) treatment (Fig. 4b). Thereafter, with the exception of the intermediate water treatment (I_3), which increased up to 80 kg/ha, there was no yield response, positive or negative, to nitrogen fertiliser.

3.4. *Crop yield/water-applied and water-use production functions*

In both years, yields increased linearly with the total depth of water ($P + I$) applied between planting and harvest. In 1988 (Fig. 5a), over the range of water inputs from about 150 to 400 mm, yields from the three treatments with additional nitrogen fertiliser (N_1, N_2, and N_3) increased by about 52($\pm$3) kg/ha for each mm of water applied as rainfall or irrigation. For the unfertilised (N_0) treatment the equivalent value was slightly higher at about 61($\pm$3) kg/(ha mm).

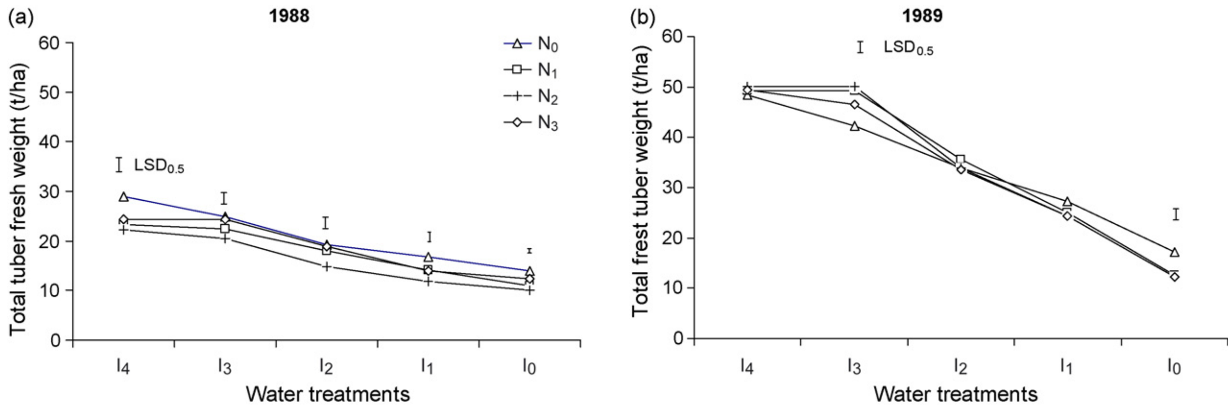

Fig. 3 – Distribution of total tuber fresh weight and total water applied as rainfall (*P*) plus irrigation (*I*) for each of four nitrogen treatments (N_0–N_3) in (a) 1988 and in (b) 1989 and for all five irrigation treatments (I_4–I_0). Values of total water applied refer to measurements made between planting and final harvest, 120 DAP in 1988 and 140 DAP in 1989.

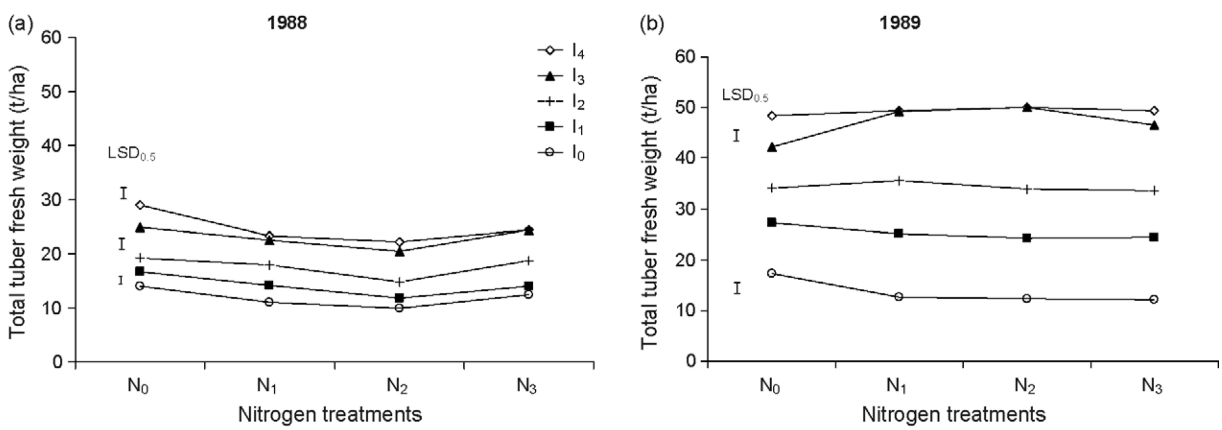

Fig. 4 – Relationships between the total tuber fresh weight and nitrogen level for each of the five water treatments: from the fully irrigated to rain-fed (I_4–I_0) in (a) 1988 and in (b) 1989. Each value of total tuber fresh weight is the mean of four replicates and refer to measurements made at final harvest, 120 DAP in 1988 and 140 DAP in 1989.

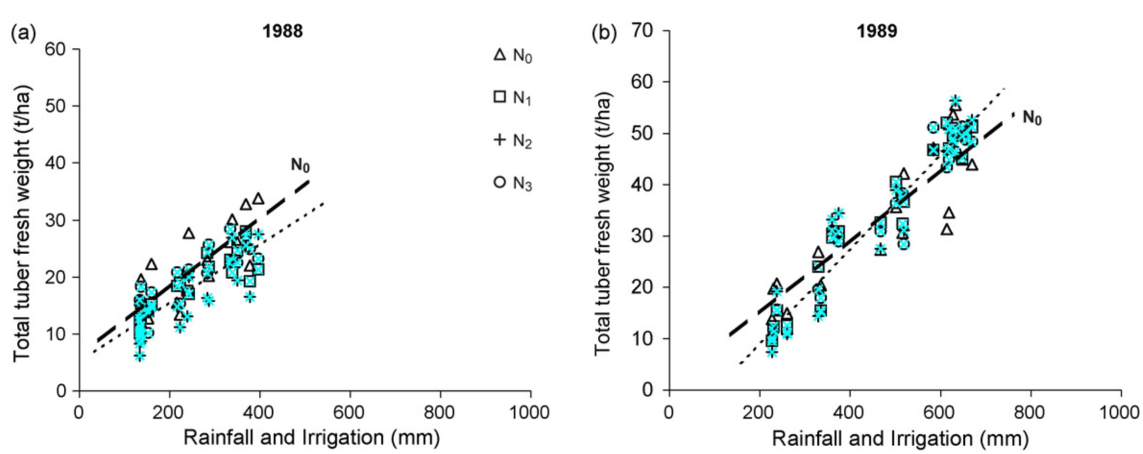

Fig. 5 – Relationships between the total tuber fresh weight and total water applied as rainfall, (*P*) plus irrigation (*I*) for each of four nitrogen treatments (N_0–N_3) in (a) 1988 and in (b) 1989 and for all five irrigation treatments (I_4–I_0). Values of total water applied refer to measurements made between planting and final harvest, 120 DAP in 1988 and 140 DAP in 1989. (For equation of lines see text).

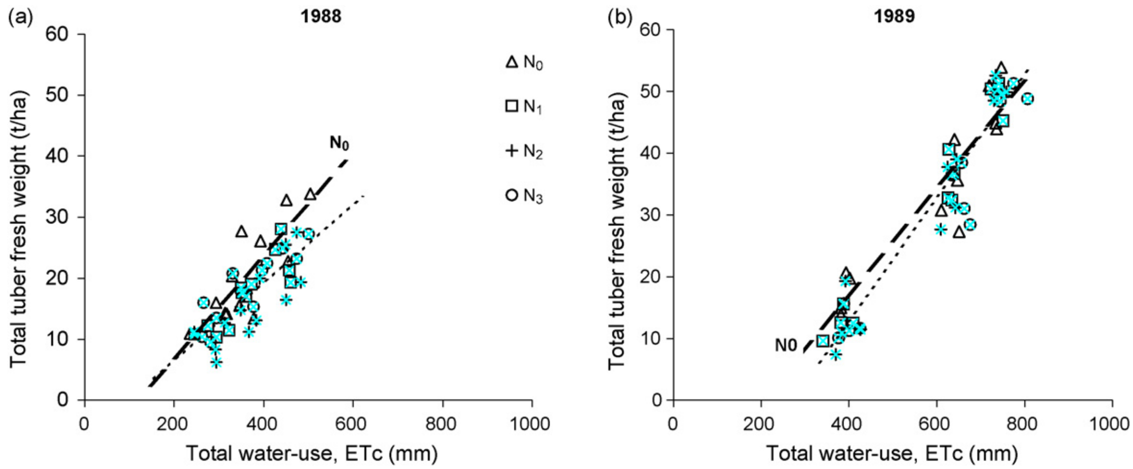

Fig. 6 – Relationships between the total tuber fresh weight and total water-use as evapotranspiration (ET_c) for each of four nitrogen treatments (N_0–N_3) in 1988 (a) and in 1989 (b) for the fully irrigated (I_4), partially irrigated (I_2) and rain-fed (I_0) treatments. Values of total water-use refer to measurements made between planting and final harvest, 120 DAP in 1988 and 140 DAP in 1989. (For equation of lines see text).

In the following year (Fig. 5b), the corresponding figures, over a larger range of water inputs (295–724 mm), were substantially more (75%) than in 1988 for the fertilised treatments, at 91(±1) kg/(ha mm), but quite similar ($P < 0.05$) for the N_0 treatment (69 ± 5 kg/(ha mm)). In each of the 2 years, the slopes of the response functions for the three nitrogen fertiliser treatments could be represented by single values. For the N_0 treatment, the response to water inputs was represented by a single value for both years (65 ± 4 kg/(ha mm); $n = 40$, $r^2 = 73\%$).

As expected, the relationships between tuber yield and crop evapotranspiration were also linear for both seasons over the ET_c range 230–500 mm in 1988 (Fig. 6a), and 330–800 mm in 1989 (Fig. 6b), where single lines again represented all three nitrogen fertiliser treatments with slopes of 64(±1) and 99(±1) kg/(ha mm), respectively. Again, for the N_0 treatment, the slopes were similar in both years and could be represented by one value 84(±5) kg/(ha mm) ($n = 24$, $r^2 = 76\%$). The intercept on the x-axis of this relationship can be used as a measure of the depth of water lost by direct evaporation from the soil surface and crop canopy before the crops had been established. In 1988, this unused water totalled about 100 mm for all four nitrogen treatments, and ranged from 200 (N_0) to 260 mm (N_1, N_2, and N_3) in 1989, representing substantial proportions of the water use from un-irrigated and partially irrigated crops.

3.5. *Yield response factor (K_y)*

In these two experiments, the largest tuber yields recorded at final harvest (Y_{max}) in single plots were 33.8 t/ha in 1988 and 53.7 t/ha in 1989. The corresponding maximum ET_{max} totals were 504 and 802 mm, respectively. The slope of the regression (K_y) between the relative yield decrease ($1 - Y_a/Y_{max}$) and the corresponding relative evapotranspiration deficit ($1 - ET_c/ET_{max}$) represents a measure of the relative sensitivity of a crop to drought in a particular environmental condition. K_y values ≥1.0 are considered to represent an actual sensitivity (Doorenbos and Kassam, 1986) to drought.

Within a given season, further nitrogen application from N_1 to N_3 did not cause significant variation of K_y values (Table 1). Surprisingly, in 1988 the slope of the regression (K_y) were greater ($P < 0.05$) for crops with no fertiliser application. By contrast, in 1989 values of K_y obtained from fertilised crops were independent of nitrogen treatment and significantly higher ($P < 0.05$) than that of unfertilised crops. Therefore, in both years, a common K_y value could represent all three treatments with additional nitrogen (N_1, N_2 and N_3), though the slopes differed, being 0.71(±0.01) in 1988 and 1.12(±0.01) in 1989. For crops which did not receive nitrogen (N_0) K_y had a similar value of 0.91(±0.04) in 1988, and 0.97(±0.01) in 1989 (Table 1).

4. Discussion

The results from the analysis of weather data collected throughout the experimental period indicate that 1988 was typically a below average growing season, being wetter and cooler than 1989. In turn, 1989 represented an above average season, that is, with drier and warmer environmental conditions than usually expected for the site. Nevertheless, the overall results show that in both seasons the generated potential soil water deficit was significant and it justified the amounts of water that were applied through irrigation, to reintegrate water losses in the soil.

The results of soil water content (θ_v) measured throughout the experimental period and shown in Fig. 2a and b confirms that soil moisture levels in the fully irrigated plots was kept below the threshold value of 50% of available water considered to be critical for maximum yield. Wright and Stark (1990) and King and Stark (1997) indicated that maximum yield of high quality potato tubers could only be achieved if the soil's available water in the maximum activity root zone would not drop below the 50% limit. Therefore, in both years, θ_v in the fully irrigated treatments (I_4) remained well above the 50% AW and water applied through irrigation and rainfall was able to

Table 1 – Relative yield response factors (K_y) shown as the relationships between the relative yield decrease ($1 - Y_a/Y_{max}$) and the corresponding relative evapotranspiration deficit ($1 - ET_c/ET_{max}$) for each of four nitrogen treatments (N_0–N_3) in 1988 and 1989 (slopes of the relationships were constrained to go through the origin[a])

Nitrogen treatment	1988		1989	
	K_y slope (a)	r^2 (%)	K_y slope (a)	r^2 (%)
N_0	0.91 a ± 0.04	66	0.97 a ± 0.01	86
N_1	0.75 b ± 0.05	74	1.13 c ± 0.04	96
N_2	0.75 b ± 0.05	69	1.19 c ± 0.03	94
N_3	0.69 b ± 0.01	79	1.10 c ± 0.03	92
Mean (N_1–N_3)	0.71 b ± 0.01	67	1.12 c ± 0.00	92
Year				*
Treatment				NS
Year × treatment				*
S.E.[b]				0.17

Each value is the mean of four replicates and refers to measurements made between planting and final harvest, 120 DAP in 1988 and 140 DAP in 1989. The regression model was of the form: $(1 - Y_a/Y_{max}) = a(1 - ET_c/ET_{max})$ ($n = 48$).

[a] Treatments within the column and between columns followed by the same letters are not significantly different (Scheffe's test at the level $\alpha = 0.05$).

[b] Standard error of year × treatment interactions.

* Significant at the $P < 0.05$ level.

reduce the soil water deficit, representing a ratio ($ET_c/ET_p = K_c$) of 0.87 (1988) and 0.85 (1989). By contrast, the data presented does suggest that in the partially irrigated plots (I_2) the water applied through irrigation and rainfall in both years, was not enough to fully compensate the water lost during a given drying cycle in order to provide the crop water requirement for normal plant production. Consequently, in these plots, to avoid acute soil water deficit plants had to extract some water that was previously stored in the soil profile, particularly towards the end on the season. Therefore, soil water content in the soil profile dropped below the critical 50% AW by 70 DAP (1988) and 78 DAP (1989). A discreet soil water deficit was then developing and increasing with time so that these crops underwent moderate stress, mainly as they reached full ground cover, resulting in a K_c of 0.60 in 1988 and 0.69 in 1989. A much greater stress was imposed upon the rain-fed treatments (I_0) especially during 1989 as most of the drought treatment period (56–110 DAP) was free from rainfall, with two odd rainfall events at the end of August and beginning of September. Crops in these treatments extracted considerably more water than those of the two irrigated treatments, as, during most of the season they had to rely solely on water previously stored in the soil for plant production. Soil water storage in both years was well below the critical 50% AW at around 60 DAP and kept falling steadily to values approaching the soils PWP. In 1989, some individual soil water storage values did fall below PWP mainly towards the end of the season. This extraction of soil water below the PWP obtained from laboratory measurements has been demonstrated to occur in crops growing in dry and hot conditions and under limited water supply (Ratliff et al., 1983; Tolk et al., 1997).

In general, the yields obtained from both seasons (Fig. 3a and b) were sensitive to water supply, whilst the yield response to nitrogen fertilisation was not significant. The imposed drought conditions significantly reduced yields of rain-fed crops to 50% (1988) and 70% (1989) of fully irrigated crops. The range of yields obtained from each of the experimental seasons also reflected the prevailing environmental conditions. During the wetter and cooler season of 1988, planting was delayed, which reduced the active growing season to only 120 days. This also reduced the total amount of water applied, as well as the time available for the crop to reach its maximum growth. Thus, yields were considerably reduced when compared to those obtained in 1989, perhaps through restrictions on the tuber bulking process. Nonetheless, the range of yields observed in both experimental years is equivalent to that reported for similar environments in Israel (Levy et al., 1990), Albacete in Spain (Fabeiro et al., 2001), Anatolian Region of Turkey (Ünlü et al., 2006) and the Bekaa plain in Lebanon (Darwish et al., 2006). Interestingly, the range of highest tuber fresh yield observed in individual plots of these experiments matches those reported so far for potatoes grown under irrigation in similar hot, dry environments: (Fabeiro et al., 2001; Wang et al., 2005; Darwish et al., 2006), irrespective of cultivar or husbandry conditions. These apparent coincidences may indicate an interesting upper yield potential for irrigated potatoes grown in such hot, dry environments of around 60 t/ha.

From these results it is also clear that mean yields of fresh tubers of crops grown under rain-fed conditions are low, varying from 12 to 14 t/ha, which reflects the observed potential soil water deficit (Ferreira and Carr, 2002) and variations of soil water content. On the other hand, these results also confirm the responsiveness of the crop to irrigation. Once subjected to irrigation, potatoes respond positively with mean maximum yields (25–50 t/ha) approaching those recorded elsewhere (Fabeiro et al., 2001; Ünlü et al., 2006; Darwish et al., 2006) for similar environmental conditions. Notably, the larger yields obtained in the fully and partially irrigated treatments in 1989 compared with 1988 were probably the result of a longer growing season due to earlier planting in 1989 and the greater overall amount of water applied.

Conspicuously, there was a consistent indication that nitrogen application tended to depress yields of unirrigated crops during both years up to 80 kg/ha of N applied. Indeed, under rain-fed conditions and in both years, significantly higher yields (30–40%) were obtained (Fig. 3a and b) from crops that were not fertilised (N_0) as compared to those crops which benefited from additional nitrogen application (N_1, N_2, and N_3). This is in agreement with results reported by Ferreira et al. (1999) for two other mountain sites in the same geographical region. These results can also be understood in the light of the recent findings from Darwish et al. (2006) which clearly indicate that application of excess nitrogen in conditions of severe water stress lowered the productivity of applied N.

Although yields of irrigated crops responded positively to N application, there was no significant and consistent response of crops to varying nitrogen levels from N_1, N_2 to N_3. These results are in accordance with those obtained by Darwish et al. (2006) in the dry Mediterranean Bekaa plain of Lebanon which indicate that there was no response from the potato crops to different nitrogen treatments at the recommended water supply of 700 mm. The results of this study do not allow to deduce what would have happen to tuber yields if the N rates were increased above the maximum (N_3, 240 kg/ha) applied in these experiments. Though during 1989 (considered a more normal growing season both in its length and climate conditions), maximum individual tuber yield (53.7 t/ha) was achieved at N_3 (240 kg/ha) and I_4 (ET_c = 569 mm) treatments, there was no significant difference between mean tuber yields of fertilised crops (N_1, N_2, and N_3) at any given water regime. Therefore, one can only speculate that, under the conditions of these experiments, N application rates *per se*, would not be the limiting factor for increasing potato tuber yields. Instead, the amount of water applied would probably be the crucial factor. Interestingly recent research on the response of potatoes yields to water and nitrogen fertilisation using similar seasonal amounts of water and N fertilisation rate lead to results similar to those obtained in 1989. Indeed, results obtained by Ünlü et al. (2006) indicate that in treatments fertilised with about 250 kg/ha of nitrogen, maximum individual tuber yield (53.3 t/ha) of potatoes was obtained in the sprinkler-irrigated treatment corresponding to ET_c = 757 mm. Furthermore, Darwish et al. (2006) concluded that in the semi-arid regions characterised by uneven rainfall, the application of 130 kg/ha of N is considered sufficient for processing potatoes.

Crop yield/water-applied production functions were determined to assess how efficiently potatoes used water that was supplied through natural rainfall (*P*) and irrigation (*I*) throughout the hot, dry growing seasons. These efficiency values (kg/(ha mm)) obtained from both season shows that they vary with nitrogen application and also with season. However, it is worth noting that crops grown only on soil's own residual fertiliser showed a more stable response between years with a mean value of about 65 kg/(ha mm). This is actually in sharp contrast with the crops that were subjected to additional nitrogen fertilisation (80–240 kg/ha of N), which responses only varied significantly with season (52–91 kg/(ha mm)). This is in accordance with other results which confirm that crop yield/water-applied production functions can actually vary with site and season (Carr, 1983) and fertiliser levels (Holmes and Stiles, 1980). Nevertheless, the actual values of yield responses to water applied obtained in this study are within the range of those reported for other hot, dry environments of 90–130 kg/ha for each mm of water applied (Ferreira et al., 1999; Kang et al., 2004; Erdem et al., 2006). Interestingly, these values though similar to those reported for other hot, dry environments, are comparatively lower than those recorded for temperate areas (UK) of 120–250 kg/ha for each mm of water applied (Harris, 1978; Carr, 1983; Jones, 1981). The reasons for the low yield responses observed in this region are not clear and neither are they for other similar hot, dry environments. Not withstanding this, the high proportion of water lost as soil evaporation (E_s) between planting and emergence in these environments may in part explain the poor performance (Ritchie, 1973). Outstandingly, in this study, E_s as a proportion of ET_c ranged between 15 and 25% in fertilised crops to 30–50% in sparsely fertilised and/or rain-fed crops (Ferreira and Carr, 2002). In relation to the apparent stability of the efficiencies obtained for the unfertilised crops, it may have to do with the soil conditions and their level of residual fertiliser. This would have probably determined that the canopy expansion rate followed a more natural course than those of fertilised crops, securing translocation of growth matter to tubers early in the season. According to Hay and Walker (1989) an increase in nitrogen supply delays leaf senescence and promotes leaf expansion. These finding have been also confirmed by Darwish et al. (2006) who found that increased N levels promoted a vigorous plant growth and less dry matter accumulation in the tubers.

Water-use efficiency of crops was determined through the relationships between tuber yield and crop evapotranspiration (ET_c) to assess how economically potatoes used the water that the crops actually took up from the soil profile. Between the 2 years, there was almost a two-fold variation ($P < 0.01$) in the mean slopes of the relationships for the three fertilised (N_1, N_2 and N_3) treatments. By contrast, values of N_1–N_3 were similar within each season. These results are in close agreement with those reported by Ferreira et al. (1999) and they may indicate that under N fertilisation, the stability of the production functions can be affected by the length of the growth period, the total depth of water applied and the air temperature. Again, under no nitrogen fertilisation, potato yield responses appear to be a constant between years, at a given altitude, responding mainly to the residual nitrogen level in the soils.

Crop sensitivity to water stress as expressed by the slope of the regression (K_y) between the relative yield decrease ($1 - Y_a/Y_{max}$) and the corresponding relative evapotranspiration deficit ($1 - ET_c/ET_{max}$), was significantly greater in 1989 than in 1988 for all four levels of nitrogen (Table 1). However, the values of K_y were unchanged by varying nitrogen levels above the residual value within a given season, but varied between seasons. Stewart et al. (1977) hypothesised that a K_y value would be a constant for a given variety and not influenced by climate. In this case, the similarity in K_y values observed within a given year, for all three fertilised crops (N_1, N_2 and N_3) and the clear variation between seasons, may perhaps indicate a negative effect of length of season or other unknown factors on tuber yield sensitivity to water stress, rather than a climate factor. However, recent attempts (Ünlü et al., 2006) to develop yield response factors for potato crops grown under two different irrigation systems in a arid location of Turkey, showed that there was no apparent effect of season or N fertilisation rates on K_y values, but varying instead with the method of irrigation from $K_y = 0.68$ (trickle) to 1.05 (sprinkler). Moreover, results obtained from other hot, dry location in Lebanon (Darwish et al., 2006), indicate a K_y value of 0.8 for potatoes grown under fertigation. These values are comparable to K_y of 0.71 (1988) and 1.12 (1989) obtained in this experiment. Nevertheless, by comparison, the pooled value of $K_y = 0.71$ obtained in 1988 is analogous to that of 0.70 reported (Doorenbos and Kassam, 1986) for potatoes when at yield formation phase. These figures may then indicate that the crop in 1988 with a shorter growing season (120 DAP) did not reach full maturity, so that the reduction in yield was proportionately less than the reduction in crop water-use irrespective of nitrogen fertilisation. In addition, the mean value of $K_y = 1.12$ obtained in 1989 is identical to $K_y = 1.15$ found for matured potato crops in hot dry conditions of Israel (Shalhevet et al., 1983). Therefore, the $K_y = 1.12$ in 1989 means that contrary to 1988 the reduction in yield was proportionately more than the reduction in crop water-use explicable by the longer growing season (140 DAP). Furthermore, the crops endured increasingly harsher soil and atmospheric conditions as the season progressed so that at full maturity, fertiliser application caused a greater sensitivity to drought ($K_y > 1.0$).

As it happens, the two growing seasons were distinct, resulting in one wetter and cooler season in 1988 and one drier and warmer season in 1989, than the long-term average. Therefore, based on this fact, the results of this study, when looked year by year, can be considered as the lower and higher base line limit for potato response to water and nitrogen fertilisation in this hot, dry environment.

5. Conclusions

From the above results, it appears that rates of nitrogen fertiliser above the levels found in the soil, seems to grossly depress yields of rain-fed crops in particular. At first sight, this may indicate that under unirrigated conditions and in soils similar to those used in this study, nitrogen fertilisation does not appear to be the major limitating factor to potato productivity, but instead, water availability to crops becomes the main issue.

These results have important implications for potato growers facing water scarcity in the region. Likewise, if the rates of fertiliser application for potato crops in this region are to be kept high, these results may indicate a latent and important environmental issue, since as mineral nitrogen is not taken-up by the crop it is more likely to become a source of pollution, feeding the drainage systems and contaminating the underground-water resources through deep percolation (leaching).

In commercial potato farming, the response functions developed in this paper, may be of great use when complemented with historical records of regional rainfall and evaporation, allowing the prediction of the likely yield increases from year-to-year. These can then be used in a detailed cost/benefit analysis to assess the worthiness of irrigation investments. Using this approach, policy makers, commercial entrepreneurs and investment bodies can make a rational evaluation of the likely yield and financial benefits from irrigation and fertilisation of potato crops in this area and in similar hot dry environment where potatoes are grown.

Finally, these results raise a question of the real advantage of nitrogen fertilisation in potato cropping in N.E. Portugal and elsewhere where soil, climate and farming patterns are similar. In itself this issue turns to be of utmost importance and deserves further research attention in the years to come, as environmental conditions in agriculture will probably worsen.

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