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Agricultural Water Management 38 (1998) 147–167

Agricultural water management

Analysis of water use by wheat grown on a cracking clay soil in a semi-arid Mediterranean environment: weather and nitrogen effects

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Accepted 13 May 1998

Abstract

Wheat (*Triticum aestivum* L.) was grown without and with nitrogen (N) fertilizer on a Vertisol at Meknes, Morocco, during two growing seasons (1993/1994 and 1994/1995) with contrasting rainfall amounts (401 and 264 mm in 1993/1994 and 1994/1995, respectively) and distribution. The effects of weather conditions and N fertilizer on water use were studied. Soil water dynamics were very different between the two growing seasons, reflecting the differences in rainfall. Water was used more efficiently for above-ground biomass production and grain yield during the 1993/1994 growing season as compared to the 1994/1995 season. Water use efficiency (WUE) for above-ground biomass averaged 36 and 5 kg dry matter (DM) ha^{-1} mm^{-1} for 1993/1994 and 1994/1995, respectively. A large difference in seasonal transpiration efficiency (TE) between the two seasons attributed partially to this. Assuming a crop coefficient, k_c of 0.0029 kPa the average TE was calculated on the basis of the mean air vapor pressure deficit (VPD) over the growing period. Transpiration efficiency was estimated at 58 and 23 kg above-ground DM ha^{-1} mm^{-1} for 1993/1994 and 1994/1995, respectively. In both seasons the most important loss of water from the profile was estimated to occur through direct evaporation from the soil. It accounted for about 35 and up to 80% of the total seasonal evapotranspiration for 1993/1994 and 1994/1995, respectively. Drainage was negligible under the given conditions. During the wettest season (1993/1994), leaf area indices (LAIs) were strongly affected by N, but this was not reflected in total water use or final DM yield. Nitrogen fertilization increased the vegetative growth, but decreased the harvest index (HI) from 33 to 27 during that season. Grain yield was not significantly affected by N fertilization. In 1994/1995

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PII: S0378-3774(98)00062-6

DM production was severely limited by the available water. No N effects were noted on water use, plant growth and grain yield in that season.

Keywords: Evaporation; Nitrogen; Soil water; Transpiration efficiency; Vertisol; Water use efficiency; Wheat

1. Introduction

Cereals are the major crops in Morocco, occupying about 80% of the total agricultural area. About 55% of the cereal production area is located in the semi-arid regions of Morocco (MARA, 1988). The Sais plateau around Meknes has a semi-arid Mediterranean climate with a temperate winter (Sauvage, 1963). In this region, wheat represents the most important crop and is essentially practised in rotation with barley, legume crops or sunflower. Up to 80% of the soils on this plateau have a minimum clay content of 40% (MARA, 1970). Crop dry matter production is mainly limited by the available soil water under the given conditions. Consequently, efficient use of the available water is very important (e.g., Cooper and Gregory, 1987). In this context, the ratio of dry matter (DM) production to crop water use (water use efficiency, WUE) is often adopted to assess the value of innovative management practices.

Under water limiting conditions the DM production depends on the volume of water transpired by the crop and the transpiration efficiency, that is, the amount of dry matter produced with a certain amount of water transpired (Ludlow and Muchow, 1990). Thus, DM production in a semi-arid environment can be improved by increasing the amount of water transpired by the crop or by increasing biomass production per unit transpiration. As grain yield depends on the amount of above-ground biomass produced and harvest index (HI), it can be improved by increasing the HI of the crop.

Several soil and crop management practices may increase the WUE and grain yield under conditions of soil water stress (Ludlow and Muchow, 1990). According to Cooper and Gregory (1987) the largest increase in WUE of rain-fed crops in the Mediterranean regions comes from altering the balance between evaporation and transpiration. A rapid canopy development achieved through N or P fertilizer application or through a higher sowing density, can result in a substantial reduction in soil evaporation and a corresponding increase in transpiration, DM production and grain yield (Cooper et al., 1987; Shepherd et al., 1987; Allen, 1990; Anderson, 1992). Van den Boogaard et al. (1996) showed that a reduction in soil evaporation early in the season at high sowing densities, did not lead to a higher grain yield. At higher sowing densities, water appeared to be more limiting later in the season as a result from the greater transpiration during the early phase of growth. Yunusa et al. (1993a, b) reported that soil evaporation is little or not affected by the size of plant canopy of spring wheat grown under the semi-arid Mediterranean conditions of Western Australia. Thus, it seems that the effects of management practices on WUE and grain yield largely depend on the local climatic and edaphic environment.

It is clear that heavy textured soils are awfully drought prone in a semi-arid environment due to the high amounts of water that are retained at wilting point.

Moreover, in cracking soils evaporation from the crack wall area occurs in addition to the evaporation from the soil surface (Ritchie and Adams, 1974).

In the experiment reported here, wheat was grown on a cracking clay soil in semi-arid Mediterranean Morocco over two growing seasons. The objective of this study was to examine the soil water dynamics and to analyze the soil water balance with respect to N fertilization and the actual weather conditions. In this paper we discuss the relationships between DM production, water use efficiency and transpiration efficiency in order to identify the factors which can improve the efficiency of growing wheat in a semi-arid Mediterranean-type environment.

2. Materials and methods

2.1. Site and climatic conditions

Field experiments were carried out during the 1993/1994 and 1994/1995 growing season at the farm of the National School of Agriculture (625 m asl, 33°52′N latitude and 5°33′W longitude), situated near Meknes on the Sais plateau of Morocco.

The climate of the Sais plateau is semi-arid of Mediterranean type with winter rainfall (Sauvage, 1963). The mean annual rainfall at the site is 526 mm (Fig. 1) and the annual potential evaporation is 1343 mm. The growing season for wheat is from mid-November to mid-June.

Data on rainfall, temperature, relative humidity, radiation and wind speed during the two growing seasons were recorded on a daily basis with a standard climatological station equipped with a CR21 Micrologger (Campbell Scientific, Logan, UT), installed at about 500 m from the experimental area. Main daily vapor pressure deficit (VPD) was calculated assuming a constant vapor pressure during the day and the relationship between saturated air vapor pressure and average daily air temperature according to Goudriaan (1977). Potential evaporation from an open water surface (E_o) was calculated according to the Penman equation, but with the modifications as described by Doorenbos and Pruitt (1977).

The soil of the experimental site is a deep heavy clay soil (Haplic Vertisol, ISSS-ISRIC-FAO, 1994). The parent material consists of lacustrine limestone. In summer the soil cracks into prisms (0.3–0.5 m across), separated by vertical cracks of up to 0.1 m width. Selected physico-chemical properties of the soil profile are given in Table 1.

2.2. Field experimental layout

The experimental design was a randomized complete block with four replicates, each plot measuring 20×25 m. The treatments were bare soil, wheat (*Triticum aestivum* L.) without nitrogen fertilization and wheat with nitrogen fertilization. In 1994/1995 an irrigated treatment was included for the cropped plots to prevent a complete crop failure due to water stress.

The wheat crop was sown at a rate of 150 kg ha^{-1}, which is a common practice in the area. A commercial seeder with a row spacing of 0.125 m was used. Seeding dates were 7

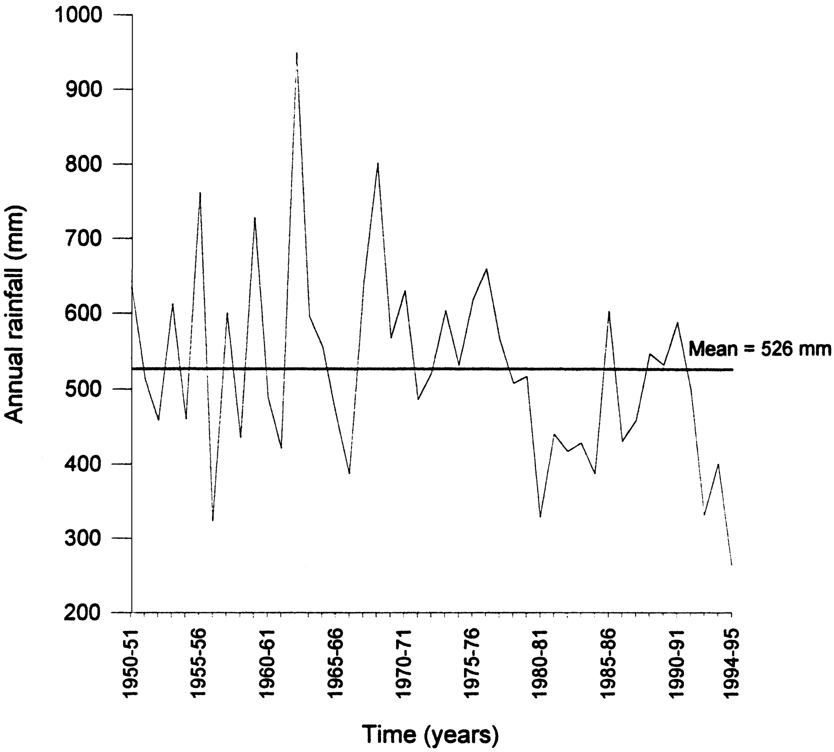

Fig. 1. Annual rainfall (1950–1994) at Meknes. Data from the National Meteorological Services, Casablanca, Morocco.

and 14 December for 1993/1994 and 1994/1995, respectively. Just before sowing, triple superphosphate (45% P_2O_5) applied at 90 kg P_2O_5 ha^{-1} and potassium chloride (60% K_2O) at a rate of 60 kg K_2O ha^{-1}, were broadcasted and incorporated into the soil using a 'covercrop'.

In 1993/1994 the N fertilized plots received 100 kg N ha^{-1} as solid fertilizer, applied in a three-split dressing as follows: (1) at seeding: 25 kg N ha^{-1} as ammonium sulfate; (2) at tillering: 50 kg N ha^{-1} as ammonium nitrate; and (3) at stem elongation: 25 kg N ha^{-1} as ammonium nitrate. During the 1994/1995 growing season, only the first N application (25 kg N ha^{-1}) took place. The N applications at tillering and stem elongation were omitted, due to the severe drought conditions. All fertilizer N was uniformly surface broadcasted by hand.

During the 1994/1995 growing season, the irrigated treatment received an irrigation of 9.2 mm, eight times during the months April and May (Fig. 2). Herbicide and fungicide applications were made to prevent sub-optimal plant growth conditions due to weed infestation or diseases. The uncropped plots were kept bare throughout the growing season by regular hand or chemical weeding. In 1994/1995 an insecticide application was necessary against trips.

Table 1
Some physico-chemical characteristics of the soil profile[a]

Depth (m)	Clay (0–2 μm[b]) (%)	Silt (2–20 μm) (%)	Sand (>20 μm) (%)	pH-H_2O	Organic C (%)	C/N	Gravimetric water content (g g^{-1})			
							At pF=2.5	At pF=4.2	At air-entry point	At swelling limit
0–0.25 – A_p	69	13	18	7.8	1.0	8.7	0.30	0.22	0.10	0.33
0.25–0.6 – B_{tss}	68	13	19	8.2	0.9	8.9	0.30	0.23	0.09	0.26
0.6–(0.75) – B_{tssk}	69	11	20	8.5	0.6	8.6	0.28	0.20	0.18	–

[a] Data are average values from two soil profiles.
[b] The particle-size analysis according to the International Soil Science Society System, was determined after decalcification with HCl.

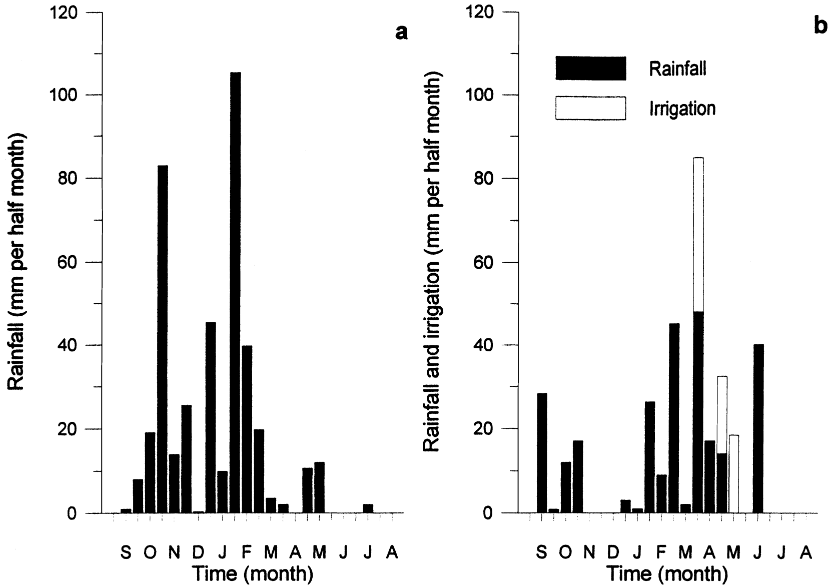

Fig. 2. Rainfall (and irrigation) distribution for the (a)1993/1994 and (b)1994/1995 growing season.

2.3. Measurements and data analysis

2.3.1. Soil bulk density

At the end of February 1994, soil bulk density was determined at different depths (up to 1 m) on bare plots of the experimental site. At that moment, the soil profile on these plots was well wetted and the measured bulk density was at its minimum. The minimum bulk density can be considered as representative for the whole soil volume, since intersecting cracks were absent. For the upper layers (0–0.2 m) the core method was used (Blake and Hartge, 1986). For the lower layers (0.2–1 m) we adopted the clod method (Blake and Hartge, 1986), since sampling problems occurred with a core sampler. The clods were dipped into petrol as water-repellent substance to calculate their volume, using Archimedes' principle.

2.3.2. Soil water

Soil moisture content was measured using a neutron meter (Hydroprobe model 503, CPN Company, Martinez, CA). On each plot one or two access tubes were installed to a depth of 1.2 m prior to sowing. As such, there were at least four replicates for every treatment. Neutron meter readings were taken in 0.15 m increments starting at 0.225 m depth and terminating at 1.125 m. The soil water content of the top 0.15 m layer was determined gravimetrically. Measurements were made 17 times in 1993/1994 and 18 times in 1994/1995. A field calibration of the neutron meter was performed on the experimental site, taking into account the bulk density effects (Greacen and Hignett, 1979). The percentage of moisture by weight was converted to percentage of moisture by volume using the calculated 'field' bulk density (Gardner et al., 1990). Field bulk density values were obtained from a combination of measured minimum core or clod bulk density when the soil showed no cracks and application of the normal isotropic shrinkage model of Fox (1964).

Changes in profile soil water content were calculated as (Yule, 1984):

$$\Delta S = \sum_{i=1}^{n} \frac{\Delta w_i \times \rho_{\mathrm{min},i} \times z_{\mathrm{ref}}}{\rho_{\mathrm{w}}} \quad (1)$$

where ΔS is the change in soil water over the considered profile depth (mm), Δw_i, the difference in gravimetric moisture content between any two sampling times for the ith depth increment (g g^{-1}), $\rho_{\mathrm{min},i}$, the minimum value of the bulk density (Mg m^{-3}) for depth increment i, z_{ref}, the depth (mm) of the soil sampling interval at minimum bulk density, ρ_{w} the density of water that is, 1 Mg m^{-3}, and n the number of depth increments, each of length z_{ref}.

Plant extractable water in the profile was calculated as the difference between the highest measured volumetric water content in the field (after 24 h drainage) and the lowest measured water content, when plant leaves are either dead or dormant (Ritchie, 1981).

2.3.3. Water use by the crop

Accumulated water use or evapotranspiration (E_{t}) was calculated by the water balance equation:

$$E_t = (P + I + C) - (R + D) - \Delta S \quad (2)$$

where P is the precipitation, I, the irrigation, C, the upward flow into the root zone, R, the surface runoff, D, the downward drainage out of the root zone, and ΔS, the change in soil water store of the soil profile considered. These quantities were expressed in terms of volume of water per unit area (equivalent depths of water in mm) during the period considered.

Water use efficiency was then calculated according

$$\mathrm{WUE_t} = \frac{\mathrm{ADM}}{E_{\mathrm{t}}} \quad (3)$$

or

$$\mathrm{WUE_g} = \frac{\mathrm{GY}}{E_{\mathrm{t}}} \quad (4)$$

where $\mathrm{WUE_t}$ is the water use efficiency for the above-ground biomass production (kg DM ha^{-1} mm^{-1}), $\mathrm{WUE_g}$, the water use efficiency for grain yield, ADM, the total above-ground DM production (kg DM ha^{-1}), GY, the grain yield (kg DM ha^{-1}), and E_{t} the total cumulative evapotranspiration (mm) over the growing season.

An estimate of the transpiration efficiency for above-ground DM production ($\mathrm{TE_t}$) was done on the basis of the following equation (Tanner and Sinclair, 1983):

$$\mathrm{TE_t} = \frac{k_{\mathrm{c}}}{\overline{\mathrm{VPD}}} \quad (5)$$

where k_c is a crop specific constant (kPa), and $\overline{VDP}$, the mean air vapor pressure deficit (kPa) over the growing period. TE_t is here expressed in kg DM ha^{-1}over kg H_2O ha^{-1}, which is equivalent to 10^4 kg DM ha^{-1} mm^{-1}.

For the crop specific constant k_c, a value of 0.0029 kPa was adapted for wheat shoot production (Yunusa et al., 1993b). Gregory et al. (1992) reported for wheat in the medium rainfall zone (>400 mm) of the Mediterranean region of Australia, values between 0.0024 and 0.0031 kPa.

The ratio of soil evaporation under crop to transpiration (E_{sc}/T) was estimated using the following equation (Cooper and Gregory, 1987):

$$WUE_t = \frac{TE_t}{1 + \frac{E_{SC}}{T}} \tag{6}$$

where TE_t is the seasonal transpiration efficiency for the above-ground DM production (kg DM ha^{-1} mm^{-1}), E_{sc}, the accumulated soil evaporation under the crop (mm), and T, the accumulated transpiration by the crop (mm).

The soil evaporation under crop (E_{sc}) and the transpiration (T) were then assessed assuming that both components are virtually independent and, therefore, additive (Denmead, 1973): $E_{sc} + T = E_t$

Values for the transpiration efficiency for grain yield (TE_g) were obtained by dividing the grain yield (GY) by the total transpiration (T).

2.3.4. Plant biomass and yield

Plant establishment was counted on 10 rows of 2 m length in each plot about 3 weeks after emergence. Leaf area was measured at different times throughout the growing season using a LI-3000 leaf area meter (LI-COR, Lincoln, NE). The leaf area index (LAI) was calculated by dividing the leaf area by the respective soil surface area.

At harvest, wheat plants from nine, 1 m^2 quadrates were hand-harvested by cutting them at soil surface level, oven dried (70°C, 48 h) and weighed. After separating the plants into straw (leaves and stem) and ears, grains were trashed from the ears and were weighed. The HI was calculated as the ratio of grain yield and total DM yield at harvest.

2.4. Statistical analysis

Statistical procedures and interpretations were based on standard methods outlined by Gomez and Gomez (1984). Data were analyzed by analysis of variance (ANOVA) using the SPSS-software (release 6.0).

3. Results and discussion

3.1. Crop growing conditions

The annual rainfall totals vary considerably in this region. Over 45 years (1950–1994), totals varied from 253 to 950 mm at Meknes (Fig. 1). The coefficient of variation in annual rainfall is 25%. Annual rainfall in 1993/1994 and 1994/1995 was 401 and

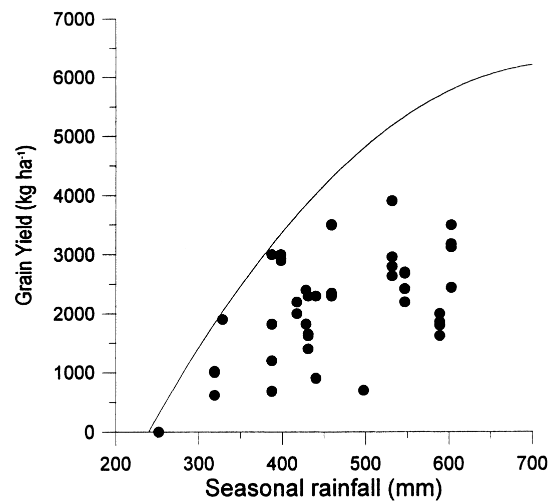

Fig. 3. Average grain yields (1985–1995) of wheat (*Triticum Aestivum* L.) in some districts on the Sais plateau around Meknes as a function of seasonal rainfall (1 September–30 June). The solid line indicates the potential yield relation calculated with the SIMTAG model (Stapper, 1984).

264 mm, respectively. The two experimental years represented the lower range of rainfall amounts.

Distribution of precipitation throughout the growing season varied largely between the 2 years (Fig. 2). The 1993/1994 season was characterized by a dry period towards the end of the wheat growing period (March–April). Moisture stress in the sensitive post-anthesis growth period is, however, common for these Mediterranean-type semi-arid regions (Smith and Harris, 1981; Yunusa et al., 1993b). The 1994/1995 season was characterized by a severe drought in winter time (November–January).

Fig. 3 shows the relationship between seasonal rainfall (1 September–30 June) and average wheat yields in some districts of the Meknes province for the period 1985–1995. In addition, the potential yield relation as derived from calculations with the SIMTAG simulation model (Stapper, 1984; Corbeels et al., 1997) is given. Farmer yields in the region are highly variable. A trend of higher yields with higher seasonal rainfall can be distinguished, at least up to 500 mm rainfall. Further, farmer yields are below the potential with a bigger deficit, a higher rainfall. The simulation analysis illustrates the large impact of rainfall amount on wheat production in this region (Corbeels et al., 1997).

The potential evaporation rate showed a distinct seasonal pattern (Fig. 4(a)). During the winter months the evaporative rate was restricted, view the low temperatures and low radiation in association with high humidity. In spring evaporation increased rapidly due to increased temperatures and radiation. Peak values, which were occasionally recorded, could be mainly attributed to high wind speeds. At the end of the wheat cropping season (mid-June) the potential evaporation rate was very high (up to 8 mm day^{-1}).

The VPD was on average higher during 1994/1995 than during 1993/1994 (Fig. 4(b)). From spring on, the VPD rose steadily and reached high values of more than 2 kPa in summer.

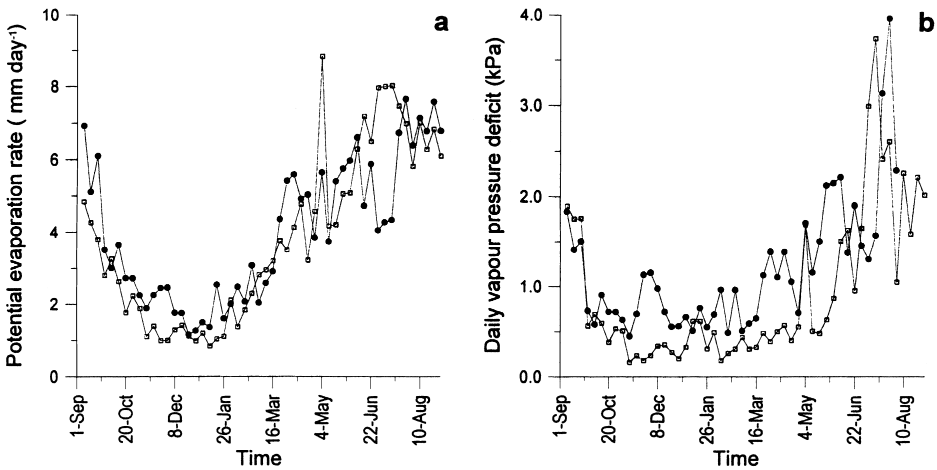

Fig. 4. (a) Potential evaporation rate (E_0) and (b) daily vapor pressure deficit for the (□) 1993/1994 and (●) 1994/1995 growing season. Values are weekly averages.

3.2. Soil bulk density

In Fig. 5 bulk density (ρ) data are plotted against soil depth. Since these data were obtained in a fully wet profile, we may consider these values as the minimum bulk densities (ρ_{min})(Gardner et al., 1990).

3.3. DM production and grain yield

The date (24 December and 17 February for 1993/1994 and 1994/1995, respectively) at which emergence took place, differed between seasons and was obviously dictated by the occurrence of the first rains after seeding. During the 1994/1995 season an abnormally long delay in emergence occurred (first rains after seeding on 10–11 February, 25.3 mm), severely hypothecating the subsequent DM production.

The number of plants established per m^2 reached nearly 100% of the seeding rate and was comparable for both growing seasons: on average 340 plants m^{-2}.

The leaf area development and maximum LAI values differed largely between the two seasons, but were only affected by N fertilization during the 1993/1994 growing season (Fig. 6). During that season, N fertilizer application increased the maximum LAI value with about 35%.

Cumulative total above-ground DM production was more than seven times higher in 1993/1994 than in 1994/1995 (Table 2), but N fertilization had no significant effect (P>0.1).

Grain yield ranged from 312±67 to 3660±100 kg ha^{-1} (Table 2). For comparison, 'on farm' average grain yields of winter wheat over the last two decades in the Sais region ranged from 0 (1994/1995) to 3180 kg ha^{-1} (1985/1986) (Provincial Direction of Agriculture (DPA) of Meknes, personal communication, 1996). Nitrogen fertilization had no significant effect (P>0.2) on the final grain yield.

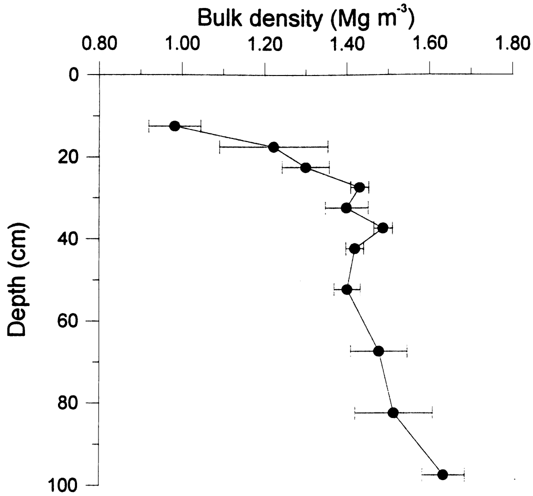

Fig. 5. Variation with depth of the minimum bulk density.

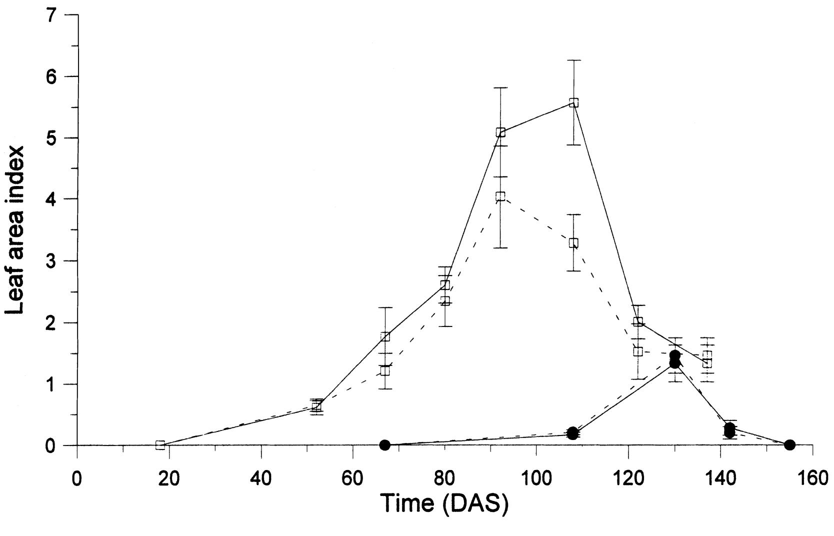

Fig. 6. Seasonal changes in leaf area of unfertilized (– – –) and fertilized (———) wheat for the (□) 1993/1994 and (•) 1994/1995 growing season (irrigated treatment). Seeding time was 7 and 14 December for 1993/1994 and 1994/1995, respectively. Vertical bars indicate ±SD.

Straw yield was significantly (P<0.1) affected by N fertilization during the wetter growing season 1993/1994. The HIs differed (P<0.05) among the growing seasons and ranged from 22 to 33. In 1993/1994, N fertilization had a significantly (P<0.1) negative effect on the HI.

Table 2
Total above-ground dry weight, grain yield, straw yield and harvest index of unfertilized and fertilized wheat grown during 1993/1994 and 1994/1995

Growing season	Fertilizer N (kg N ha^{-1})	Total above-ground DM (kg DM ha^{-1})	Grain yield (kg DM ha^{-1})	Straw yield§ (kg DM ha^{-1})	Harvest index
1993/1994	0	11013±357[a]	3660±100[a]	5616±436[a]	33.2±1.7[a]
	100	11913±473[a]	3224±443[a]	7112±268[b]	27.1±2.0[b]
1994/1995 (rain-fed)	0/25[b]	1084±153	0	ND	0
1994/1995 (irrigated)	0	1446±194[a]	312±67[a]	763±80[a]	21.6±2.0[a]
	25	1786±367[a]	401±153[a]	870±117[a]	22.4±1.7[a]

[a] Vegetative plant parts (=total above-ground DM minus grain and chaff DM).
[b] Average values for fertilized and unfertilized plants.
Different letters indicate significant differences at 10% level between the two N fertilizer levels.
ND, not determined.

3.4. Soil water dynamics

Seasonal net changes in total water content of the soil profile (0–1.2 m) are given in Fig. 7. The soil water dynamics for the two seasons were very different, reflecting the differences in rainfall amount and distribution.

The soil moisture pattern during the 1993/1994 growing season (Fig. 7(a)) was characterized by an important profile recharge during winter (25–90 days after seeding, DAS). During these cool months, rainfall exceeded evapotranspiration and water was stored in the profile. Maximum profile recharge (400–450 mm) was recorded at the beginning of March (90 DAS). Profile recharge under wheat was very similar to that under fallow, since recharge occurred when crop leaf area (Fig. 6) and thus transpiration were small. Consequently evapotranspiration was dominated by evaporation from the soil. From spring on, when air temperature, radiation and canopy development increased, the evaporative demand exceeded rainfall. As a result soil profiles lost their water continuously up to crop maturity and harvest. This observed pattern of soil profile wetting and depleting is typical for soils under cereals in a semi-arid Mediterranean-type of environment and has also been observed by others (Perrier, 1973; Gregory et al., 1984; Cooper et al., 1987; Van den Boogaard et al., 1996).

Although not significant (P>0.1), a tendency of lower soil moisture contents under fertilized crops in comparison with unfertilized crops could be distinguished. It was also noted that even under fallow an important discharge occurred during the growing season (about 16% of the maximal recharge).

The 1994/1995 growing season showed not such a pronounced moisture recharge and discharge pattern, due to the severe drought during winter (Fig. 7(b)). Evidently, no effect of N fertilization on the soil water dynamics was observed. The spring rains did not recharge the profile, because of the high evaporative demand at that period.

Fig. 8 gives a picture of the changes in volumetric moisture content at discrete depth intervals with time for the two growing seasons. In 1993/1994, under fallow, the recharge

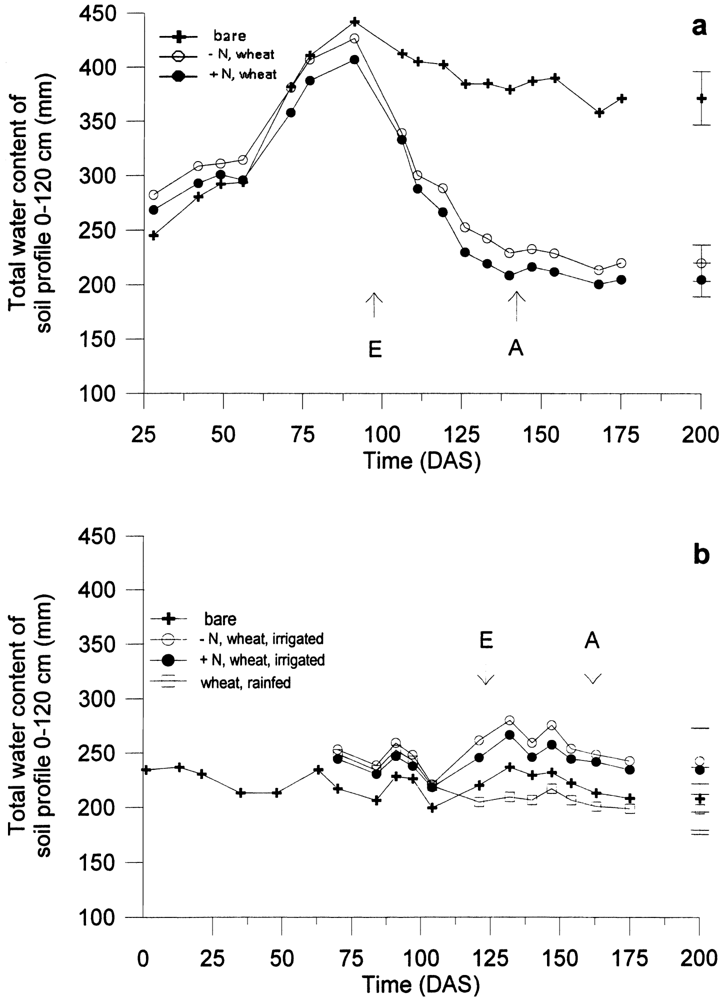

Fig. 7. Seasonal changes in amount of total soil water for the (a) 1993/1994 ((+) bare soil, (○) unfertilized wheat and (•) fertilized wheat)) and (b) the 1994/1995 season ((+) bare soil, (○) unfertilized irrigated wheat, (•) fertilized irrigated wheat and (□) rain-fed wheat, average values for unfertilized and fertilized treatment). Seeding time was 7 and 14 December for 1993/1994 and 1994/1995, respectively. Vertical bars indicate the mean SD. E: stem elongation. A: anthesis.

front went through the bottom of the 1.2 m profile and drainage losses occurred (Fig. 8(a)). Following the date of maximal recharge (90 DAS), a profile discharge up to 0.45 m depth was recorded under fallow. Under planted conditions, rewetting occurred to a depth of approximately 1.2 m. Fertilized crops tended to dry out the soil to a greater extent. Discharge occurred to a depth of approximately 1 m under unfertilized wheat, while under fertilized wheat soil moisture was depleted to about 1.2 m at maturity. However, this N effect was not significant ($P>0.1$). It was also observed that the upper

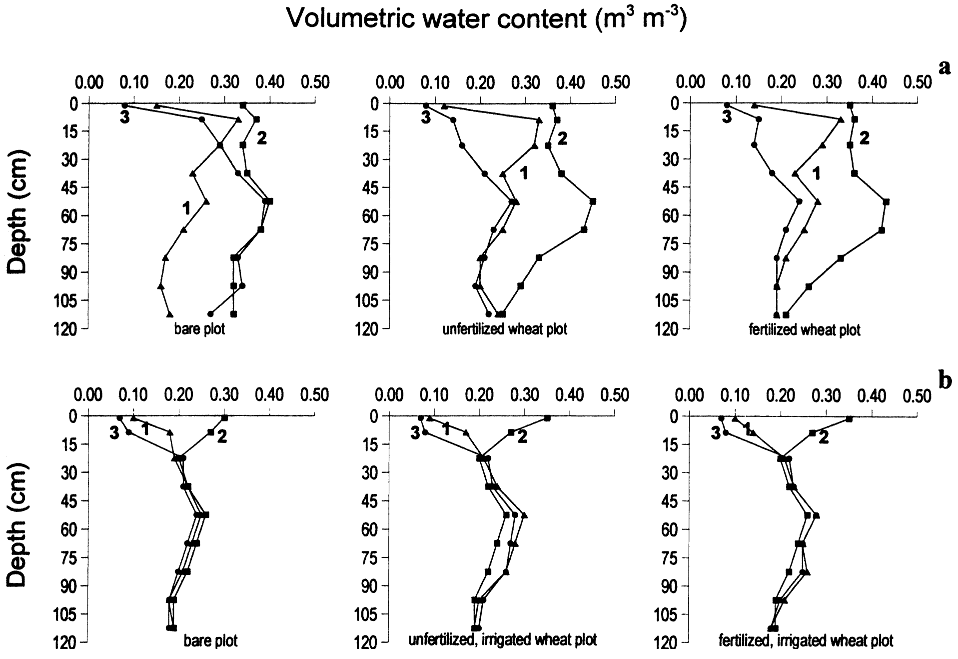

Fig. 8. Distribution of volumetric moisture content with depth at different times during the (a) 1993/1994 and (b) 1994/1995 growing season for different treatments. Line 1 indicates the moisture distribution at seeding time, line 2 at maximum profile recharge and line 3 at harvesting time.

horizon was slightly wetter at seeding time than at maturity. This was due to the occurrence of early autumn rains before seeding.

In 1994/1995 the moisture profiles showed only small changes (Fig. 8(b)). Roots were unable to extract stored water at depths greater than 0.5 m during that season.

It is characteristic for these clayey soils that significant amounts of moisture were lost even under fallow, presumably by the high evaporative fluxes from cracks. Ritchie and Adams (1974) showed in a lysimeter experiment on a bare soil that only small amounts of water leave the soil through the dry surface layer in comparison to the amount of water evaporating from the wetter soil along the walls of the shrinkage cracks below the surface. The efficiency of moisture storage by fallowing will thus largely depend upon the occurrence of cracks. Therefore, the use of crop residues is beneficial both by preventing excessive soil cracking and reducing evaporative losses (Yule, 1984).

On heavy clay soils moisture stress during grain-filling is particularly pronounced because of the large gap between the air-dry water content (8%) and the water content at wilting point (>20%). After a dry period with high evaporative demand – as late in the season during grain-filling – very large water deficits develop in the surface soil and large amounts of rain are needed to raise the water content above wilting point. Moreover, part of the rainfall water may flow down as free water through cracks into the deeper layers. This means that under the given conditions late season rains will rarely be effective for grain production.

Table 3
Extractable soil moisture (mm) under wheat grown with and without fertilizer in 1993/1994 and 1994/1995

Depth (m)	1993/1994		1994/1995[a]	
	0 kg N ha^{-1}	100 kg N ha^{-1}	0 kg N ha^{-1}	25 kg N ha^{-1}
	Extractable soil moisture (mm)			
0.00–0.15	22.3	22.8	21.8	20.2
0.15–0.30	35.1	35.5	2.3	0.9
0.30–0.45	29.8	30.7	1.5	1.6
0.45–0.60	31.2	32.3	0.1	0.1
0.60–0.75	31.4	35.2	–	–
0.75–0.90	28.3	27.6	–	–
0.90–1.05	23.4	17.7	–	–
1.05–1.20	11.9	11.6	–	–
Total	213.4	213.4	25.7	22.8

[a]Irrigated treatment.

3.5. Plant extractable water

Extractable water was about nine times higher in 1993/1994 than in 1994/1995 (Table 3). In both seasons, N fertilization had no effect on the amount of extractable water. It is clear that the amount of extractable water was largely determined by the depth of water extraction, which was dictated by the depth of the recharge front.

Variable results on the effect of fertilizer on the ability of cereals to extract water are found in previous investigations under similar climatic conditions (Gregory et al., 1984; Cooper et al., 1987; Shepherd et al., 1987). It seems that the amount and distribution of rainfall is distinctive. Higher amounts of extractable water under fertilized crops are usually ascribed to the positive effect of fertilizer application on root growth (Cooper et al., 1987). This is surely true in situations where roots extend throughout the wetted part of the soil profile. In this way the larger root system will consume a greater volume of the stored water.

3.6. Evapotranspiration

In this study surface run-off was non-existing or negligible and thus ignored. The slope of the experimental site was less than 0.5%. Upward flow of considerable amounts of water into the root zone was also assumed to be negligible. The water table was at a depth of about 25 m. Nevertheless, the profile of extractable water of the 1993/1994 growing season (Table 3) suggests an extraction of some small amounts of water from a depth >1.2 m. On the basis of the moisture profile distributions of Fig. 8, drainage losses were considered to be negligible under cropped conditions for both growing seasons. This is evidently so for the 1994/1995 growing season, whereas for the preceding season, any occasional drainage below 1.2 m would have been small and, if occurring, at least partly recovered by the crop. Evapotranspiration was thus calculated as the difference between precipitation (and irrigation) and changes in total moisture content in the profile (Eq. (2)).

Table 4
Some components of the water budget of winter wheat grown at Meknes in 1993/1994 and 1994/1995 (irrigated and rain-fed) with and without N fertilization

	1993/1994		1994/1995		
			Irrigated		Rain-fed[a]
	0 kg N ha^{-1}	100 kg N ha^{-1}	0 kg N ha^{-1}	25 kg N ha^{-1}	
Maximum LAI (m^2 m^{-2})	4.0	5.5	1.4	1.6	ND
$\overline{VPD}$ (kPa)	0.50	0.50	1.25	1.25	1.25
E_o (mm)	522	522	615	615	615
E_t (mm)	317	316	271	279	241
E_{sc} (mm)	127	111	209	202	194
T (mm)	190	205	62	77	47
E_{sc}/T	0.67	0.54	3.37	2.62	4.13
WUE_t (kg DM ha^{-1} mm^{-1})	34.7	37.7	5.3	6.4	4.5
WUE_g (kg DM ha^{-1} mm^{-1})	11.5	10.2	1.1	1.4	0
TE_t (kg DM ha^{-1} mm^{-1})	58.0	58.0	23.2	23.2	23.2
TE_g (kg DM ha^{-1} mm^{-1})	19.3	15.7	5.0	5.2	0

[a]Average values for fertilized and unfertilized plants.
ND, not determined.

The total seasonal evapotranspiration (E_t) was, averaged over the two N treatments, 317, 275 and 241 mm, respectively for 1993/1994, the irrigated treatment in 1994/1995 and the non-irrigated treatment in 1994/1995 (Table 4).

For comparison, the total potential evaporation (E_o) from an open water surface (Doorenbos and Pruitt, 1977), was 522 and 615 mm for the period from seeding till harvest for 1993/1994 and 1994/1995, respectively (Table 4).

Nitrogen fertilization had no effect on the cumulative crop evapotranspiration for both growing seasons (Table 4). This means that a higher LAI, as induced by fertilization (1993/1994), doesn't necessarily result in a significantly higher cumulative evapotranspiration, presumably due to the restricted water availability under the given conditions.

Contrasting data on the effect of N fertilization on total crop evapotranspiration in semi-arid regions are found in the literature (Campbell et al., 1977; Gregory et al., 1984; Cooper et al., 1987; Shepherd et al., 1987; Allen, 1990; Anderson, 1992; Yunusa and Sedgley, 1992). Positive effects of N fertilization on E_t were principally related to the stimulation of both above-ground biomass and root growth with more interception of incoming solar radiation. This results in a higher transpiration requirement, while at the same time more soil water is made available through the root proliferation, provided adequate soil water is available.

About 80 and 75% of the total water use occurred before anthesis, respectively for the 1993/1994 and 1994/1995 growing season (data not shown). French and Schultz (1984) reported on the basis of 61 field trials that more than 70% of the total water use occurred before anthesis for wheat grown in the Mediterranean-type area of Australia. The ratio of water use before and after anthesis is the very determinant for the HI and the final grain yield of cereals grown under semi-arid Mediterranean conditions (Fischer, 1979). There is experimental evidence that crops produce the largest grain yields at ratios between 2:1 and 3:1 (French and Schultz, 1984; Anderson, 1992). A large contribution of stored pre-anthesis assimilates to the grain yield can stand at least partly for the reduced post-anthesis transpiration and assimilation (Palta and Fillery, 1995). However, a ratio of 4:1 seems to induce under the given conditions a too important stress during grain-filling (1993/1994), as reflected by the low HIs (Table 2).

3.7. Water use efficiency

Values for WUE_t and WUE_g are presented in Table 4. WUE_t in 1993/1994 (on average 36 kg DM ha^{-1} mm^{-1}) was substantially higher than in 1994/1995 (on average 6 kg DM ha^{-1} mm^{-1}). In 1993/1994, N fertilization resulted only in slightly, not significantly, higher WUE_t values. The non-irrigated wheat in 1994/1995 showed the lowest WUE_t value (4.5 kg DM ha^{-1} mm^{-1}).

Similarly, WUE_g values showed large differences between seasons, but no significant effect of fertilizer was observed. Since non-irrigated wheat produced no grains in 1994/1995, WUE_g for grain production was 0.

Van den Boogaard et al. (1996) reported WUE_t values between 38 and 43 kg DM ha^{-1} mm^{-1} for wheat grown under medium (>300 mm) and low rainfall (<300 mm) conditions of Northern Syria, respectively. The WUE_g was 13 and 15 kg DM ha^{-1} mm^{-1}, with the higher value for wheat grown under low rainfall conditions. Values obtained by French and Schultz (1984) for wheat in the Mediterranean-type conditions of Australia ranged between 10 and 37 kg DM ha^{-1} mm^{-1} for WUE_t and between 2 and 13 kg DM ha^{-1} mm^{-1} for WUE_g.

3.8. Transpiration efficiency and balance between E_{sc} and T

TE_t values differed greatly between the two seasons. The 1993/1994 values were about two times higher than those of 1994/1995 (Table 4). Under a Mediterranean environment, where saturation deficits increase steadily during spring and early summer (Fig. 4(b)), the delayed phenological development of wheat in 1994/1995 resulted in a plant experiencing higher VPD at any given development stage, and thus achieving lower transpiration efficiencies (Eq. (5)). The estimated value for TE_t during the 1993/1994 season, was comparable with the average value (54 kg DM ha^{-1} mm^{-1}) reported by Yunusa et al. (1993b) for spring wheat growing in the Mediterranean-type region of Australia. French and Schultz (1984) obtained a maximum TE_t of 55 kg DM ha^{-1} mm^{-1} in a series of wheat trials in southern Australia.

Concerning N effects, it is not expected that N fertilization would directly affect the transpiration efficiency, since transpiration efficiency is based on physiological processes (Ludlow and Muchow, 1990).

At the end of the growing seasons, the cumulative evaporation losses from the soil under cropping conditions were large (Table 4). Soil evaporation (E_{sc}) from cropped plots during the 1993/1994 season was estimated between 111 (fertilized crops) and 127 mm (unfertilized crops). In 1994/1995, E_{sc} was more than 200 mm, both in the irrigated and non-irrigated treatment. Apparently, late season rain and irrigation water quickly evaporated.

Transpiration (T) as a proportion of total evapotranspiration was about 60 (unfertilized plants) and 65% (fertilized plants) in 1993/1994 and is comparable with data from Cooper et al. (1987) and Van den Boogaard et al. (1996) for wheat under similar conditions in Syria. During 1994/1995, cumulative transpiration amounts accounted only for about 20 (non-irrigated) and 25% (irrigated) of the total evapotranspiration. These latter values are low and of the same order as the data reported by Pilbeam et al. (1995) for maize grown in semi-arid Kenya. The lower transpiration observed with the non-irrigated cropped treatment was largely due to the early senescence of the rain-fed plants.

The failure of N fertilization – in spite of its effect on LAI (1993/1994) – to considerably modify E_{sc}, E_{sc}/T and consequently WUE, suggested that, when differences in LAI values between N treatments were observed, the second-stage drying, that is, the water limited evaporation stage (Ritchie, 1972), dominated largely the evaporative losses. Ritchie and Burnett (1971) reported that the crop canopy needs to intercept about 90% of the incident radiation to significantly suppress E_{sc}. This interception threshold value corresponds with a LAI value >4, assuming an extinction coefficient of 0.5 (Monteith, 1965). Such high levels of LAI are observed in 1993/1994 only from about 90 DAS (March) on, presumably when second-stage drying (energy-limited evaporation) dominated the evaporation process. The period of frequent rainfall (January–February), when the soil surface was constantly wet and first-stage drying took place, was associated with low LAI levels. During the 1994/1995 season, the crop canopies were too small to achieve a considerable control on E_{sc}.(Daamen et al., 1995).

4. Conclusions

Wheat DM production and grain yield varied considerably between the two growing seasons, largely depending on the seasonal water dynamics and thus on the amount and distribution of seasonal precipitation. Rainfall exceeded water use only during the first part of the growing cycle. Under the given climatic conditions a possible N fertilization effect appears in the first place through an increased LAI and vegetative biomass production. For the final grain development, wheat relies greatly on the remaining water stored in the soil.

Drainage losses were minimal under cropped soil conditions. Consequently, the balance between evaporation from soil and transpiration by plants determines largely the crop productivity in this region. Due to the cracking properties of the soil, considerable evaporative losses occurred up to 0.45 m soil depth. Efforts to alter the balance between evaporation and transpiration, through N fertilization inducing a larger plant cover, have a limited effect on the WUE and final grain yield, since possible early positive effects on E_{sc}/T are set off during grain-filling. Moreover, the predominance of second stage soil evaporation during the growing season limits the suppressing effect of LAI on the E_{sc} losses.

In an environment, where VPD increases steadily throughout the growing season, early plant establishment and plant growth is beneficial in terms of TE and WUE. Hence, the importance of early seeding in this region. Selecting varieties with early development is another means of increasing TE. Furthermore, under the given conditions an increase in the WUE and hence crop productivity can also be achieved from the reduction of soil evaporation. In this context mulching with crop residues or zero tillage are two options. Recent trials in the Meknes region testing the no tillage practice with retention of crop residues have shown some promising results, indicating an increase in grain yield of about 20% (Boutahar, 1996).

Acknowledgements

This research was part of a collaborative project between the University of Ghent (RUG) (Belgium) and the Ecole Nationale d'Agriculture (ENA) at Meknes (Morocco). The authors would like to thank the Belgian General Administration for Development Cooperation for their financial support. They are also grateful to members of the technical staff at ENA for their help with fieldwork. Finally, we also thank the anonymous referees for their most useful comments.

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