Irrigation treatments, water use efficiency and crop sustainability in cereal-forage rotations in Mediterranean environment

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Abstract

Agricultural systems based on crop rotation are beneficial to crop sustainability and productivity. Wheat-forage rotations combined with irrigation are the agronomic techniques best able to exploit Mediterranean environmental conditions. This paper describes a long-term field trial to ascertain the effect of combined irrigation and durum wheat forage rotations on crop yield and soil chemical properties. The two forage crops, annual grass-clover winter binary mixture and perennial lucerne, were carried out through 1991-2008 under rainfed and irrigated treatments. The experiments were performed to highlight the effect of irrigation and wheat-forage crop rotations on water use efficiency (WUE) and sustainability of organic matter (OM) in topsoil. Irrigation increased the dry matter (DM) of annual binary mixture and lucerne by 49.1% and 66.9%, respectively. Continuous wheat rotation reduced seed yield (SY), stability of production, and crude protein (CP) characteristics of kernel and OM in topsoil. The yearly gain in wheat after forage crops was 0.04 t (ha yr^{-1}) under rainfed and 0.07 t (ha yr^{-1}) under irrigation treatments. The CP and soil OM of wheat forage crops rotations, compared with those of continuous wheat under rainfed and irrigated was a 0.8 and 0.5 % increase in CP and 5.1% and 4.4% in OM, respectively. The rotations of annual grass-clover winter binary mixture and lucerne meadow under both irrigated treatments increased the OM over continuous wheat (9.3% and 8.5% in annual grass-clover winter binary mixture and 12.5% and 9.5% lucerne meadow under rainfed and irrigation, respectively). Irrigation reduced the impact of weather on crop growing, reducing water use efficiency (mean over rotations) for DM production {15.5% in meadow and 17.5% in annual grass-clover winter binary mixture [L water (kg DM)$^{-1}$]} and wheat SY. However, the agronomic benefits achieved by forage crops in topsoil are exhausted after three years of continuous wheat rotation.

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Key words: annual grass-clover winter binary mixture, durum wheat, irrigation, lucerne meadow, Mediterranean environment, soil chemical parameters, wheat-forage rotations.

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Introduction

Crop rotation is an indispensable agronomic practice able to preserve the ecological functions and sustainability of environments and topsoil fertility. Experiments based on crop rotation have highlighted the positive effects on crop yields and ecosystem sustainability (Martiniello, 2007; Cui *et al*., 2009; Tilman *et al*., 2009). However, particularly in environments with a Mediterranean-type climate in which water resource availability may be a limiting factor, long-term crop rotation is essential to sustain the turnover of soil chemical properties.

Relationships between irrigation and crop rotation treatments interfered with water use efficiency (WUE) of crops influencing agronomic quality and productivity of the crops and microbial activity of topsoil (Martiniello, 2007; Cui *et al*., 2009; Shahriar, 2009). Technological and social evolution in the last century resulted in intensive farming systems with simple agronomic crop management, causing drastic consequences on the sustainability of soil organic matter (OM) and stability and quality of crop production (García del Moral and Rharrabti, 2007; Tilman *et al*., 2009). The environmental impact of intensive agriculture may be reduced by adopting alternative farm management practices which recognize the benefits involved for the quality of overall products and sustainability of soil ecology (De Vita *et al*., 2007; Cui *et al*., 2009; Tilman *et al*., 2009).

This study was set out to assess the effect of 18-year wheat forage crop rotation experiments, under rainfed and irrigated conditions, upon crop WUE, productivity, yield stability and product quality characteristics and OM sustainability in the topsoil under Mediterranean weather conditions.

Materials and methods

Field trial

The experiment was set up at the Menichella farm of the Agricultural Research Council located in Foggia (41°31' N; 15°33' E) through the period 1991 to 2008. The soil was a Chromic Vertisol (FAO-

ISRIC-ISSS, 1998) in arid climatic conditions with a depth Ap (over 200 cm). The soil texture and hydrological characteristics prior to the beginning of the experiment, in the 0-35 cm Ap horizon, were: coarse sand (2-0.2 mm) 200 g kg^{-1}; fine sand (0.2-0.02 mm) 350 g kg^{-1}; silt (0.02-0.002 mm) 190 g kg^{-1}; clay (<0.002 mm) 260 g kg^{-1}; pH (water) 8.1; cation exchange capacity 456 cmole g^{-1}; active carbonate 47.5 g kg^{-1}; total nitrogen 1.43 g kg^{-1}; OM 25.1 g kg^{-1}; available phosphorus 26 mg kg^{-1}; C/N 9.8 g kg^{-1}; and exchangeable potassium 1388 mg kg^{-1}. The content of nitrogen and phosphorous in the soil are low while those of potassium is high. Thus, nitrogen and phosphorous were integrated by chemical fertilizer for sustaining crop production while potassium is not supplied during the cultivation of the crops. The following properties of soil were determined by cylindrical test core according to the methodology reported by Arshad *et al*. (1996): bulk density (1.242 g cm^{-3}), wilting point (18%), total water availability (25%) and readily available water (7%). The physical, chemical and hydrological parameters of soil were determined according to the following laboratory procedure: Day (1965) for texture and pH; Kjeldahl (1983) for nitrogen; Walkley and Black (1934) for OM; Olsen *et al*. (1954) for phosphorous; UNICHIM (1985) for potassium; Druineau (1942) and Géhu and Franck (1959) for active carbonate and electric cation exchange capacity; and Richards and Ogata (1961) for the hydrological parameters. Mean climatic data (1990 to 2008) related to mean temperature, precipitation, evapotranspiration from a Class A water pan evaporimeter and global radiation occurred in the location, where the experiment was established, are shown in Table 1.

Durum wheat (DW), annual grass-clover winter binary mixture (BM) and lucerne meadow (LM) crop rotations were established under two water regimes (irrigated and non-irrigated, the latter being referred to henceforth as rainfed). The average number of watering and the amount of water supplied to crops under irrigation are reported in Table 1. The experiment was arranged in a split plots in space and time design with irrigation as whole plots and rotations as subplots. To minimize the interaction effect of genotype, agronomic treatments and environment, the varieties used in the experiments remained the same throughout the period of evaluation (Table 2). Three randomized replicates were drawn up in a subplot. There were 78 plots of experiments in all (39 under irrigated and as many as under rainfed). The specific rotations evaluated every year were: three years of BM (berseem clover, *Trifolium alexandrinum* L. + barley, *Hordeum vulgare* L.) after three years of continuous wheat (1-yr BM, 2-yr BM and 3-yr BM); 3-yr LM (*Medicago sativa* L.) LM after wheat continuously grown for 3-yr (1-yr LM, 2-yr LM and 3-yr LM); and seven DW (*Triticum durum* Desf.) rotations [continuous wheat for all period of experiment (CDW); 3-yr continuous wheat after a 3-yr old meadow (1-yr DWLM, 2-yr DWLM and 3-yr DWLM); 3-yr continuous wheat after a 3-yr continuous BM (1-yr DWBM, 2-yr DWBM and 3-yr DWBM)]. The rotation of old LM and continuously BM at 2 and 3 year, since they are used for preparing the rotation of DWt after forage crops, are not considered in the analysis of data. The acronyms of wheat and forage crops rotations of the experiment used in the text, figures and tables are reported in Table 3.

Throughout the trial years seedbeds (1990-2007) of DW, BM and 1-yr LM rotations were prepared using a mouldboard plough that tilled soil to a depth of 35 cm in the 3rd week of September. The ploughed soil was smoothed with a field cultivator and tine harrow a week later. Straw from all DW rotations was removed from the plots before ploughing. Every year DW and BM rotations were fertilized in mid September during seedbed preparation using nitrogen and phosphorous fertilizers. In February, when the DW crop was at the beginning of the heading stage, a top dress-

Table 1. Mean of meteorological parameters during the 18 years of evaluation, standard deviation of the means and lowest and highest values of the meteorological event.

Source	Mean temperature (°C)	Rainfall (mm)	ET (mm)	Radiation (MJ m^{-2} y^{-1})	Waterings (n)			Water supply (mm ha^{-1})		
					DW	BM	LM	DW	BM	LM
Mean	16.1	444.1	1684	5236	3.8	3.9	12.6	189	192	632
Standard deviation	0.2	32.5	32	105	0.1	0.2	0.3	6	7	15
Value										
Lowest	14.3	248.4	1513	4714	3	3	10	150	150	150
Highest	17.3	597.3	1897	5827	4	5	14	200	250	700

ET, evapotranspiration; DW, durum wheat; BM, binary mixture; LM, lucerne meadow.

Table 2. Cultivar, seed density and fertilizer used in the experiment.

Crop	Cultivar		Inorganic fertilizer applied to crop			
	Name	Seed density (kg ha^{-1})	Seedbed		Top dressing	
			Nitrogen (kg ha^{-1})	Phosphorous (kg ha^{-1})	Nitrogen (kg ha^{-1})	Phosphorous (kg ha^{-1})
Durum wheat	Ofanto	200				
	In all rotations		30	31.3	60	
Binary misture			30	31.3		
Two rowed barley	Arda	80				
		In all rotations				
Berseem	Sacromonte	40				
		In all rotations				
Meadow						
Lucerne	Equipe	40		38.9		40
		In 1-yr rotation		In 1-yr rotation		In 2-yr and 3-yr rotations

ing fertilizer was applied. The 1-yr LM rotation was fertilized at seedbed preparation and the 2-yr LM and 3 -yr LM, were top dressed with phosphorous in the last week of February. The amount of fertilizers applied to the crops at seedbed and at top dressing are shown in Table 3. Plots of rotation treatments were 12 m long and 8 m wide under irrigated and 6 m long and 4 m wide under rainfed conditions. Every replication of DW, BM and 1-yr LM rotations, since the second week of October 1990, was planted by drill experimental equipment. The sowing of DW and 1-yr LM rotations was made in equal spaced rows 17.5 cm apart and in alternate equally spaced rows the BM rotations. The characteristic and seed density of cultivars, utilised for all period of experiment, were reported in Table 2. The water content in the top 15 cm layer soil was measured according to the procedure reported by Oweis *et al*. (2000). Evapotranspiration (ET) was determined from sowing to harvest of crops according to the following soil water balance ET= S [variation in soil water storage (mm)] + P [rainfall (mm)] + I [irrigation (mm)]. Soil water storage was measured by neutron probe (mm) before and after irrigation supply. The probe, with high-energy neutrons, gagged in the soil according to the recommendations of Hanson *et al*. (2007), emits radiations rating of 50 millicurries/m enabling the gauge to monitoring soil moisture content. During the experiment, drainage and runoff were absent. Water was applied when the cumulative daily evapotranspiration from Class A water pan, corrected by appropriate standard single crop canopy factor (kc), reached 80 mm (Doorenbos *et al*., 1979). The average of kc value of irrigation applied in spring, summer and autumn months was approximately 1 (one). In addition, in the last five years a complete agreement was found between the ET values determined by the meteorological instruments and those simulated by the Decision Support System embedded in the AQUATER software for irrigation management in semi-arid Mediterranean environments (Acutis *et al*., 2010). Crop WUE [L water (kg DM)$^{-1}$] was defined as ratio of DM crop production to ET and determined according to the procedure described by Rinaldi and Ubaldo (2007). The WUE in the rainfed experiment was determined by dividing the DM stem (whole DM and SY stem in DW and DM stem in LM and BM) by the rainfall felt during the growing season while the WUE of the irrigated experiment was assessed dividing the DM and SY stems by the rainfall occurred during the trial plus ET derived from water supplied by irrigation to the DW, LM and BM rotations (Table 1). Irrigation was carried out with a horizontal bar 16 m long, 125 cm above the soil surface, applying a fixed volume of water (500 m^3 ha^{-1}). Nozzle pressure was 0.19 MPa and the apparatus was moved by a hydraulic system. The watering apparatus ensured uniform water coverage and distribution on the plots. Mean total volume of water and number of irrigations applied to the DW, BM and LM rotations, are reported in Table 1. Crop growth under irrigation was completed in the second week of June for DW and the last week of July for the BM and throughout the year for LM while the growing of the rotations under rainfed treatment finished in the first week of June. To avoid the border effect, the harvest of forage biomass DM and cereal grains was made in the centre of replication entries (18 and 10 rows, respectively, for irrigated and rainfed treatments), using experimental plot combines. The harvest of LM was established when more than 80% of tillers in the plot had flowered, while the herbage biomass of BM was cut at barley heading in the harvest made before April and after this month, at the flowering of berseem clover. Forage biomass DM (t ha^{-1}) at harvest was assessed on fresh herbage from each experimental plot. The DM at harvest was determined from a sample of about 500 g of fresh forage, dried at 65°C with forced ventilation for 72 h and then weighed to determine moisture content. On each DW rotation plot were assessed the traits grain yield (SY, t ha^{-1} at 13 g kg^{-1} standard moisture content) and DM of whole stem and seed stem weight. The above ground biomass of DM stem (DM stem, g stem^{-1}) and SY stem weight (SY stem, g m^{-2}) was determined on samples of tillers picked from two 0.5-m sections of rows harvested prior to threshing the plot.

Laboratory determinations

Kernel crude protein

The parameter was assessed on plot seed samples. After harvest a sample of about 1000 g of kernels was air-dried in a chamber with forced ventilation and stored at a cool room temperature of 4°C. The parameter was determined using the near-infrared (NRS) spectroscopy technique with a Foss NIRSystem monochromator scanner 6500 active in the range of 400-2500 nm (FOSS, NIRSystems, Inc., Laurel, MD, USA). The samples used for calibration were analyzed using a laboratory standard official method for determining CP concentration. The calibration equation was validated using analyzed DW flour obtained from ground seed with a Cyclotec 1093 sample mill (Tecator AB, Höganäs, Sweden) with a mesh screen of 1 mm of diameter.

Soil organic matter

In September 1990 and in November 2008 (beginning and end of the rotation experiments), soil samples were harvested for physicochemical determinations. The samples were taken from the soil surface (0-35 cm Ap horizon) using a 60 mm diameter core sampler. Twelve soil samples were harvested at the start of the experiment at each grid point, on the surface where rainfed and irrigated plot treatments of the experiment were established. The grid soil sampling procedures revealed systematically soil composition and consist in splitting the surface of experimental plot in square cells where soil core sample, at the middle of the shape, was collected. The source of soil sample for chemical analysis was built blending the soil harvest from cores (Ferguson *et al*. 2009). At 12 grid points of the experimental area of the beginning and in each plot of the rainfed and irrigated treatment at end experiment, soil samples were collected. The total numbers of soil samples harvested during the experiment were 90 (12 at the beginning, 39 under rainfed and as many for the irrigated treatment).

Each soil sample was made by mixing four soil cores drilled from grid points of the plot surface, after thorough manual root separation, were air-dried and then sieved with a squared 2 mm mesh screen and kept in cool room at 4°C. The soil samples harvested at the beginning, prior to laboratory determination, were kept at -20°C and those collected at the end of the experiment in a cool room at 4°C. The OM was determined according to Walkley and Black (1934) laboratory method.

Table 3. Acronym of crops and rotation treatments used in the experiment.

Acronym of treatment Durum wheat (DW)	Description of rotation
CDW	Continuous wheat
1-yr DWLM	1-yr DW after a 3-yr old LM
2-yr DWLM	2-yr continuous DW after a 3-yr old LM
3-yr DWLM	3-yr continuous DW after a 3-yr old LM
1-yr DWBM	1-yr DW after a 3-yr continuous BM
2-yr DWBM	2-yr continuous DW after a 3-yr continuous BM
3-yr DWBM	3-yr continuous DW after a 3-yr continuous BM
Lucerne meadow (LM)	
1-yr LM	1-yr LM
2-yr LM	2-yr old LM
3-yr LM	2-yr old LM
Binary mixture (BM)	
1-yr BM	1-yr BM
1-yr BM	2-yr continuous BM
1-yr BM	3-yr continuous BM

Statistical analyses

The weather factors occurred during the period of experiment interfered with experimental treatments generating a statistical size effect which rendered the data of experiment not independent and as consequences not statistically valuable. To make data of experiment stochastically independent were analyzed with meta-analysis statistics according to Hedges (1981). The method use standardised mean effect size in the order to eliminated scale difference among datum according to Fan and Hancock (2012) robust means modelling procedure. The analysis is basically computed as difference score between single data and the overall mean of experiment dived by the pulled error of ANOVA.

Statistical analysis of standardised data of experiment of all traits were analysed according to factorial design and was conducted separately for DW, LM and BM crop by using the PROC ANOVA procedure of the SAS (1997). The model adopted for analysing the SY and kernel CP characteristic of DW, was a factorial experimental design with a split plots in space (irrigation and rotation treatments) and time (year of evaluation) where year, irrigation and rotation were assumed as the first, second and third factors of the analyses (Steel and Torrie, 1980). The level of each factor was: 18 per year in SY and 4 in kernel CP, 2 for irrigation and 7 for rotations. ANOVA uses a mixed model with irrigation as a fixed effect and year of evaluation and replication as random effects. The statistical analysis of BM and LM crops is processed separately. The ANOVA of BM and LM, with common harvests (first two harvests) under rainfed and irrigated conditions, were processed according to factorial design with the following priority of factor: year, irrigation, rotation and harvest with 18, 2, 3 and 2 levels, respectively. Furthermore, the ANOVA of BM and LM data made under irrigated treatment was performed according to split plots in space and time factorial design with year as the first factor, rotation the second and harvest the third with levels 18, 3 and 3 in BM and 18, 3 and 6 in LM, respectively. Relationship among linearity components of rotation treatments under rainfed and irrigated treatment were determined by multiple linear regression analysis according to PROC REG of the SAS (1997). The analysis was assessed on the year mean of replications of biagronomical, kernel CP and topsoil OM of DW and DM and DM stem of LM and BM characteristics under rainfed and irrigated rotations. The significance of determination coefficient (R^2) was tested comparing the value of analysis with those of the tabulated Student's *t*-test at the appropriate freedom degree. The values of multiple linear regression coefficient equation and determination coefficient (R^2) are reported on Figures 1 to 4. The linear equation

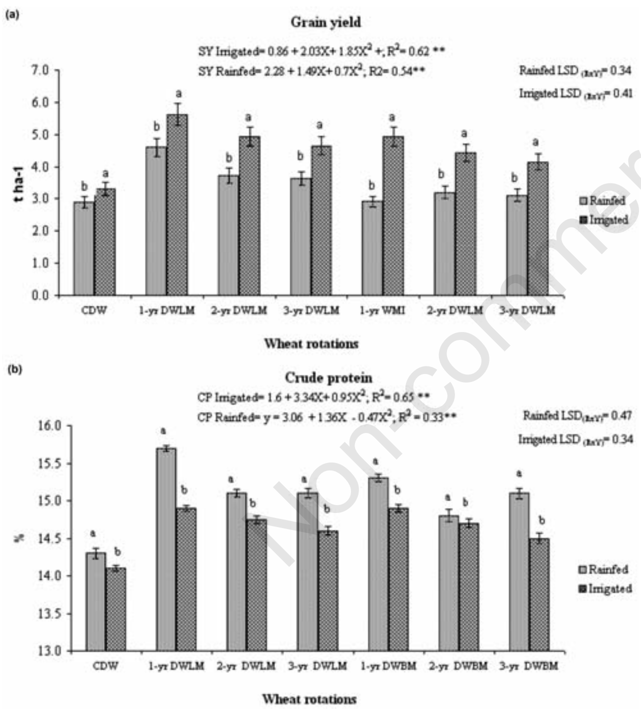

Figure 1. Yearly mean of 18 years in seed yield (a) and 5 years in crude protein content (b) of wheat forage crop rotations (CDW, 1-yr DWLM, 2-yr DWLM and 3-yr DWLM, 1-yr DWBM, 2-yr DWBM and 3-yr DWBM) under rainfed and irrigated conditions in rotation experiment in Mediterranean environment; CDW, continuous wheat. *,: determination coefficient (R2) significant at 0.05 and 0.01 level of probability, respectively. Bars of rainfed and irrigated rotations with the same letter not statistically differed at Duncan's multiple-range test at P>0.05 level of probability. Vertical line on the bar of rainfed and irrigated treatment represents the range of standard deviation of the means across the period of evaluation. LSD(RxY) interaction value was the least significant difference at P>0.05 probability level among rotations of rainfed and irrigated treatment.**

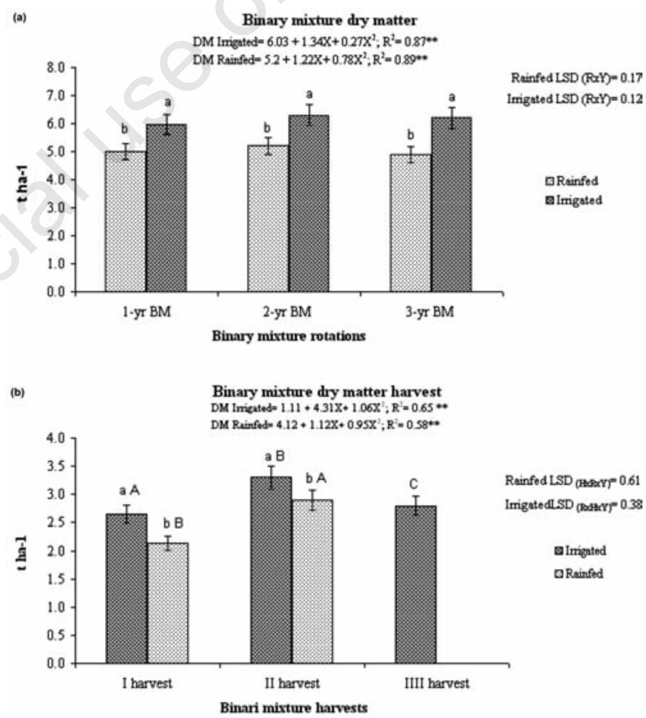

Figure 2. Yearly mean of 18 years in dry matter binary mixture rotations (1-yr BM, 2-yr BM and 3-yr BM) under rainfed and irrigated condition and yearly mean dry matter harvests of rainfed (a) and irrigated treatments (b) of the 1-yr BM, 2-yr BM and 3-yr BM rotations experiment in Mediterranean climate; BM, binary mixture. *,: determination coefficient (R2) significant at 0.05 and 0.01 level of probability, respectively. (a) Bars of rainfed and irrigated rotations 1-yr BM, 2-yr BM and 3-yr BM with the same letter not statistically differed at Duncan's multiple-range test at P>0.05 level of probability; vertical line on the rainfed and irrigated bar represents the range of standard deviation of the means across the period of evaluation. (b) Bars of the harvest of 1-yr BM, 2-yr BM and 3-yr BM rotations with same small letter under rainfed and capital letter under irrigated, are statistically not different at Duncan's multiple-range test range at P>0.05 level of probability. LSD(RxY) and LSD(HxRxY) interaction values of the least significant difference at P>0.05 probability level of the harvests under rainfed and irrigated treatment.**

components of the independent explanatory variables (rotation and irrigation treatments in all graphs of figures, except the graph b in Figure 2 and Figure 3, where the variables were: rotation, irrigation and harvest), were determined for each trait under rainfed and irrigated condition. Comparison involving rotations pair means of irrigated and rainfed treatment reported in all figures, was made according to Duncan's multiple-range test while difference among rotation treatments under rainfed and irrigation treatment by Least Significant Difference (LSD) computed utilizing the RxY interaction mean square of the ANOVA analysis (Steel and Torrie, 1980) (Tables 4 and 5). The means comparison of harvests in BM and LM forage crops under rainfed and irrigated treatment were made by Duncan's multiple-range test and the harvest of rotation treatments by LSD assessed utilizing the HxRxY interaction mean square (Table 6). The means comparison of WUE in DM and SY stem in DW and DM stem in BM and LM rotations of 1-yr, 2-yr and 3-yr of were made by LSD computed on the base of IxRxY interaction meansquare reported in Tables 4 and 5. The effect of rotation on SY stability of DW was determined according to Eberhart and Russell (1966). The stability of SY is based on regression analysis determined using SY data of CDW, DWLM and DWBM rotation treatments over the period of the experiment on an independent index computed from environmental factors (soil fertility, temperature, rainfall, ET and global solar radiation). The stability of SY is defined by: mean of rotation treatments over the period of evaluation, regression coefficient (b, response of rotation to weather conditions) and deviation from regression (S^2d, standard deviation of mean of rotation treatments through the period of evaluation). The statistical significance of the regression coefficient of the rotation effect on SY was tested with Student's *t*-test values with 112 degrees of freedom, dividing the S^2d value by the residuals from individual regressions (pooled error) (Steel and Torrie, 1980). The soil OM trait of the rotation treatments was analyzed according to a split plot design model with irrigation in the main plot and rotation in the subplots with three replications. Mean comparison value among rotation treatments was tested with the appropriate statistical test (rotation under rainfed and irrigated treatment, by Duncan's multiple-range test and rotation treatments under rainfed and irrigated condition by LSD).

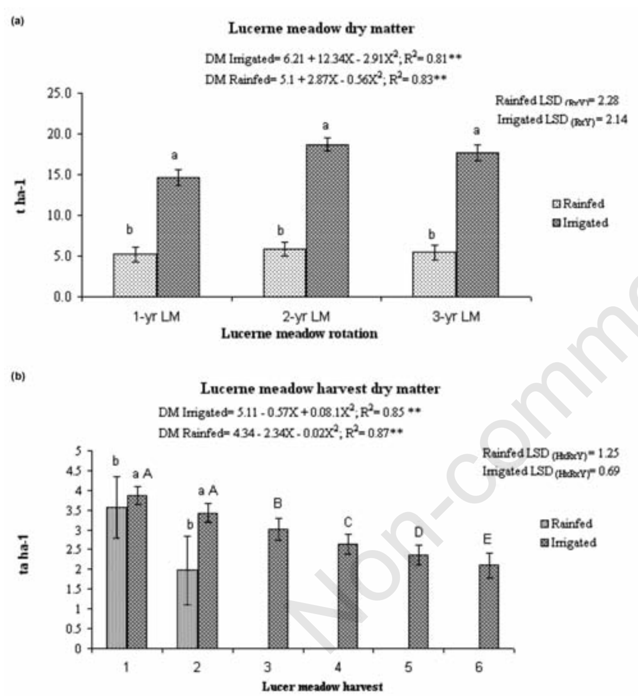

Figure 3. Yearly mean of 18 years in dry matter lucerne meadow rotations (1-yr LM, 2-yr LM and 3-yr LM) under rainfed and irrigated condition and yearly mean DM harvests of rainfed (a) and irrigated treatments (b) of the 1-yr LM, 2-yr LM and 3-yr LM rotations experiment in Mediterranean climate; LM, lucerne legume. *,: determination coefficient (R2) significant at 0.05 and 0.01 level of probability, respectively. (a) Bars of rainfed and irrigated 1-yr LM, 2-yr LM and 3-yr LM rotations with the same letter not statistically differ at Duncan's multiple-range test at P> 0.05 level of probability; vertical line on the rainfed and irrigated bar represents the range of standard deviation of the means across the period of evaluation. (b) Bars of the harvest 1-yr LM, 2-yr LM and 3-yr LM rotations with same small letter under rainfed and capital letter under irrigated, are statistically not different at Duncan's multiple-range test range at P>0.05 level of probability. LSD(RxY) and LSD(HxRxY) interaction values of the least significant difference at P>0.05 probability level of the harvests under rainfed and irrigated treatment.**

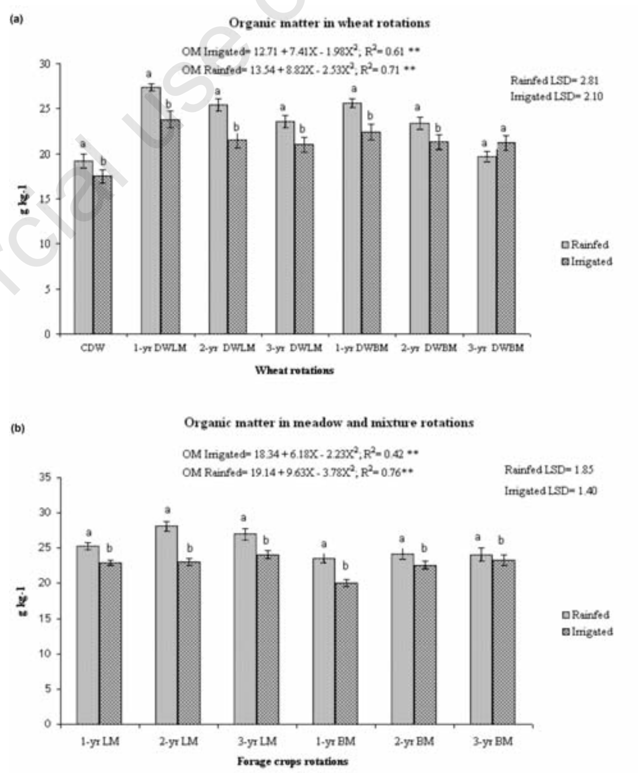

Figure 4. Organic matter content in topsoil at end of experiment in wheat forage crop rotations (CDW, 1-yr DWLM, 2-yr DWLM 3-yr DWLM, 1-yr DWBM, 2-yr DWBM and 3-yr DWBM) under rainfed and irrigated conditions (a) and lucerne meadow (1-yr LM, 2-yr LM and 3-yr LM) and binary mixture (1-yr BM, 2-yr BM and 3-yr BM) rotations (b) under rainfed and irrigated conditions in a Mediterranean environment; CDW, continuous wheat. *,: determination coefficient (R2) significant at 0.05 and 0.01 level of probability, respectively. Bars of rainfed and irrigated rotation with the same letter not statistically differ at Duncan's multiple- range test at P>0.05 level of probability. Vertical line on the rainfed and irrigated bar represents the range of standard deviation of the means across the period of evaluation. LSD(RxY) interaction value was the least significant difference at P>0.05 probability level among rotations of rainfed and irrigated treatment.**

Results

Durum wheat

The SY of CDW under both irrigated treatments was stimulated by DWLM and DWBM rotations as indicated by a linear and quadratic response of multiple linear regression analysis (Figure 1a). Analyses based on multi linear regression revealed that the variation recorded in the SY and CP traits of wheat forage crop rotations under both rainfed and irrigate condition, was mainly associated with linear effects (52 and 48% SY and 78 and 22% in CP under irrigated and 78 and 22% SY and 68 and 32% in CP under rainfed in linear and quadratic effect, respectively) (Figure 1a,b).

In all traits, the ANOVA revealed a significant effect of the main factor: year, rotation and irrigation treatments. The absolute variation of mean square values of rotation over irrigation treatments was a consequence of the higher effect of wheat rotation than irrigation treatments (Table 4). The lack of statistical significance observed in the two-way (IxR, irrigation x rotation) and (RxY, rotation x year) and three-way interaction factors (IxRxY, irrigation x rotation x year) in some SY component traits (seed spike^{-1}, harvest index and test weight) were ascribed to relationships among experimental factors with weather conditions which influenced the adaptability and the development of the crop in the environment (*data not shown*).

Irrigation reduced the impact of weather on physiological processes of crop development, leading to higher DM production and WUE than rainfed conditions (Table 7). The effect of CDW rotation reduced the mean of SY by 4.7 and 25.6% under rainfed and 26.1 and 34.7% under irrigated treatments in comparison to those of DWBM and DWLM, respectively (Figure 1a).

The mean values over the years of 1-yr, 2-yr and 3-yr rotations under rainfed of DWBM and DWLM increased SY of CDW rotation. The beneficial effect of DWLM and DWBM (1-yr, 2-yr and 3-yr mean) rotation treatments on CDW increased SY by 28% and 6.7% under rainfed and 33.8% and 24.3% under irrigated treatment, respectively (Figure 1a). A similar trend was observed for irrigation on 1-yr, 2-yr and 3-yr DWLM rotations (18.1%, 25.3% and 25.3% in comparison to those under rainfed, respectively) (Figure 1a).

The lower WUE of 1-yr DWML and DWBM of SY rather than 2-yr and 3-yr rotations in DWLM and DWBM under rainfed and irrigated treatments showed that the beneficial advantages of forage crop rotations expired its effect in 2-yr and 3-yr in both DWLM and DWBM rotations (DWLM: 20% and 22.6% under rainfed and 10.8% and 16.7% under irrigated, respectively while in DWBM, the reduction was evident only under irrigated conditions:10.3% and 18.2%, respectively) (Figure 1a and Figure 4b; Table 7). However, the higher WUE recorded in DWLM and DWBM rotations under irrigated rather than those of rainfed, was due to the delayed period of threshing caused by irrigation treatment (Table 7). The combined effect of rotation with irrigation upon SY was higher in 1-yr DWLM than those of 2-yr and 3-yr DWBM (11.9% and 17.1%, respectively) and in all rainfed DWLM rotations (Figure 1a). The agronomic effect of irrigation and rotation upon SY (t ha^{-1}) in DWBM

Table 4. Mean squares and significance effect of wheat forage crop rotations on trait seed yield, dry matter stem and seed yield stem under rainfed and irrigated condition in Mediterranean environment.

Source	df	SY (t ha^{-1})	DM stem (g m^{-2})	SY stem (g m^{-2})	Source	df	CP %
Year (Y)	17	4.5 **	31.1 *	25 *	Year (Y)	3	4.1 *
Irrigation (I)	1	17.7 **	213 **	233 **	Irrigation (I)	1	0.4 **
Rotation (R)	6	23.7 **	159 **	105 **	Rotation (R)	6	20.2 **
Interaction					Interaction		
IxY	17	0.7 **	204 **	57 **	IxY	3	7.2 **
RxY	102	1.4 **	62 **	28 **	RxY	18	7.4 **
IxR	6	6.9 **	242 **	57 *	IxR	6	4.5 **
IxRxY	102	0.9 **	24 **	70 **	IxRxY	18	1.8 **
Pooled error	504	0.2	14	12	Pooled error	112	0.4

df, degree of freedom; SY, seed yield; DM, dry matter. *Significant at 0.05 probability level; ** significant at 0.01 probability level.

Table 5. Mean squares and significant effect of forage crop rotations on dry matter and dry matter stem traits of binary mixture and legume lucerne crops under rainfed and irrigated condition in Mediterranean environment.

Source	df	DM BM (t ha^{-1})	DM plant BM (g m^{-2})	DM LM (t ha^{-1})	DM plant LM (g m^{-2})
Year (Y)	17	12.5**	7.8**	1.4*	31.3**
Irrigation (I)	1	805.6**	52.1**	1906.8**	433.3**
Rotation (R)	2	10.1 ns	2.7 ns	5.1**	318.5**
Harvest (H)	1	263.5**	13.8*	12**	213.4**
Interaction					
HxY	17	16.5**	12.5**	13**	15.6**
IxY	17	8.5*	23.5**	10.0**	16.4**
RxY	51	10.9**	29.7**	5.8**	4.9*
IxR	2	4.5 ns	22.9**	4.2**	16.3**
HxIxR	2	8.4 ns	21.1**	2.3**	7.6**
IxRxY	14	8.3*	10.5*	2.5**	8.8**
Pooled error	164	3.7	3.3	0.3	2.41

df, degree of freedom; DM, dry matter; BM, binary mixture; LM, lucerne meadow. *Significant at 0.05 probability level; ** significant at 0.01 probability level. ns, not significant.

rotations in comparison to those of DWLM was reduced by 25.2% and 11.9% under rainfed and irrigated conditions, respectively. Furthermore, the SY of 1-yr DWLM under irrigation was 12.1% and 19.8% higher than that of 2-yr and 3-yr rotations, respectively while under rainfed, the effect of 1-yr DWBM rotation was reduced in 2-yr and 3-yr DWBM (3.4% and 2.7%, respectively) (Figure 1a).

The effect of irrigation on rotation treatments of DWLM, DWBM and CDW rotations emerging from the regression analysis of Eberhart and Russell (1966) reduced the weather impact on crops over 18 years of evaluation (Table 8). The higher values of b and S^2d of CDW rotation under rainfed than those of irrigated (0.82 and 0.63 in b and 280.1** *vs* 75.1* in S^2d, respectively), was attributed to reduced environmental impact of the irrigated treatment on plant development across the years of evaluation. Greater benefits from DWLM and DWBM rotations were achieved in 1-yr of rotation under rainfed treatment whose mean SY increased over CDW by 38.9% in DWLM and by 5.1% in DWBM and reduced the b and S^2d values (b, 0.82, 0.72 and 0.78 and S^2d, 280.1**, 78.2* and 98.2* in CDW, 1-yr DWLM and 1-yr DWBM, respectively).

The better SY performance under rainfed of DWLM and DWBM rotations than those of CWD, was achieved by the increase of OM in topsoil which buffered the impact of environment on plant development (Figure 4a). However, under rainfed the agronomic effect of 1-yr DWLM and 1-yr DWBM on SY stability and SY production was weakened in the 2-yr and 3-yr DWLM and DWBM rotations. The reduction in mean SY in CDW, in comparison to DWLM and DWBM under rainfed and irrigated conditions, was due to a reduction in OM in topsoil (Figure 1a and Figure 4a). The content of kernel qualitative chemical characteristics was related to DW forage rotations rather than irrigated treatments. The qualitative characteristics values of seeds CDW, DWLM and DWBM rotations under irrigation treatment were lower than those of rainfed. Furthermore, the discrepancy among traits of 1-yr, 2-yr and 3-yr DWLM under rainfed and irrigated treatments was lower than those of DWBM (*data not shown*). However, among qualitative kernel parameters, the CP was the trait which showed significant correlation r values with SY under both rainfed and irrigated treatment (0.48** and 0.66** with n = 26 df, respectively). The different pattern of CP content in CDW, 1-yr, 2-yr and 3-yr DWLM and DWBM rotations under rainfed and irrigated treatments showed that the relocation process of CP to the kernel was related to weather and agronomic management (Figure 1b). The CP mean value of CDW was lower 5.7% and 4.9% under rainfed and 5.2% and 4.2% under irrigated treatment than the values recorded in DWLM and DWBM, respectively (Figure 1b). The mean CP of CDW and the mean over DWLM and DWBM under rainfed was 1.4%, 2.0% and 1.8% higher than those of irrigation treatment, respectively (Figure 1b).

Forage crops

The DM production across 1-yr, 2-yr and 3-yr BM and LM rotations was favoured by irrigation treatment. The ANOVA of the common I and II harvests under rainfed and irrigated treatment of BM and LM rotations, revealed mean square values of irrigation factor higher than those of year, rotation and harvest (Table 5). The linear component of multiple linear regression equation of DM production under irrigated

Table 6. Mean square significant effects of rotation and harvest treatments on dry matter and dry matter stem traits of binary mixture and legume lucerne crops under rainfed and irrigated condition in Mediterranean environment.

		Rainfed				Irrigated			
Source	df	DM BM (t ha^{-1})	DM LM (t ha^{-1})	Source	df	DM BM (t ha^{-1})	Source	df	DM LM (t ha^{-1})
Year (Y)	17	12. **	12.3**	Year (Y)	17	12.5**	Year (Y)	17	28*
Rotation (R)	2	71.1 ns	88.1*	Rotation (R)	2	70.1*	Rotation (R)	2	54.7*
Harvest (H)	1	941.5*	1592.1*	Harvest (H)	2	67.5*	Harvest (H)	5	29.7**
Interaction				Interaction			Interaction		
HxY	17	9.5*	13**	HxY	34	5.5*	HxY	115	24.2**
RxY	51	5.9*	7.5*	RxY	34	60.9**	RxY	34	5.6*
HxR	2	17.4 ns	88.6*	HxR	2	67.4*	HxR	10	9.1**
HxRxY	34	70.6*	14.0**	HxRxY	34	5.6*	HxRxY	170	10.9**
Pooled error	199	3.7	4.5	Pooled error	360	3.1	Pooled error	618	2.6

df, degree of freedom; DM, dry matter; BM, binary mixture; LM, lucerne meadow. *Significant at 0.05 probability level; ** significant at 0.01 probability level. ns, not significant.

Table 7. Water use efficiency in dry matter and seed yield stem traits of continuous wheat, 1-yr, 2-yr and 3-yr DWLM, DWBM, LM and BM rotation treatments under rainfed and irrigated conditions in Mediterranean environment.

	Water use efficiency [L water (1 kg DM)$^{-1}$]									
	Rainfed					Irrigated				
Rotation	CDW	1-yr	2-yr	3-yr	LSD	CDW	1-yr	2-yr	3-yr	LSD
Wheat-meadow										
DM stem	39	36	34	36	*	48	38	39	41	*
SY stem	152	96	120	124	**	192	115	129	138	**
Wheat-mixture										
DM stem		35	37	38	*		44	44	47	*
SY stem		143	148	147	**		130	145	159	**
DM stem LM		85	77	81	**		74	62	61	**
DM stem BM		94	88	89	**		81	60	78	**

CDW, Continuous wheat; LSD, Least Significant Difference; DM, dry matter; SY, seed yield. *Significant at 0.05 probability level; **significant at 0.01 probability level.

condition was higher than rainfed (Figure 2a and Figure 3a). The reduced DM production of LM than BM across harvests under rainfed was a consequences of different adaptability of the crops to the weather environment. The different fitness of LM and BM crops was evidenced by inverted values of linear and higher quadratic components in the linear equation ($1.12X + 0.95X^2$ in BM and $-2.34X + 0.02X^2$ in LM, respectively) (Figure 2b and Figure 3b).

The effect of weather during growing on LM in comparison to BM, instead irrigation, caused decrease of linear and quadratic components of multiple linear equation (4.31X and 1.06X2 in BM and – 0.57X and + 0.08X2 in LM, respectively) achieving a decline of DM production through the harvests (Figure 2b and Figure 3b). The reduced mean square values of the irrigation treatment observed in DM in BM, in comparison to those of LM, evidenced wide adaptability of the LM to weather conditions of Mediterranean climate (Table 5). The mean square variability among two- (IxY, irrigation x year; HxR, harvest x rotation) and three-way (IxRxY, irrigation x rotation x year) interaction factors resulted from different effects of agronomic treatments on regrowth during the period of evaluation (Table 5).

The DM trait of BM, in comparison to those of LM, as effect of vegetative stasis, lack the statistical significance in the two- (IxY and HxR) and three-way (IxRxY) interaction factors (Tables 5 and 6). The DM mean of 1-yr, 2-yr and 3-yr LM rotations of rainfed was 19.7% lower than those of irrigated and showed a reduced variation among rotations in both irrigation treatments (Figure 2a). The lack of significance in DM of two- (IxR, IxY and HxR) and three-way interaction factors (HxIxR) showed linear relationships among BM rotations under rainfed and irrigated treatment (R^2 =0.87** and 0.89**, respectively), evidencing that the factors harvest, irrigation and rotation treatments did not interfere with plant development (Figure 2a; Table 6). Analogous relationships were found in the mean of DM values of rotations in the harvests under irrigated. The about similar determination coefficient values recorded among rainfed and irrigated condition (R^2 =0.65 ** and 0.58 **, respectively) harvests of LM rotations, evidenced that DM was not influenced by both rotations and irrigation treatment (Figure 2b).

The variation of yearly DM in LM under rainfed and irrigated treatments were linearly correlated with irrigated rather than rotation treatments (Figure 3a). The yearly DM mean of LM rotations in the harvests under rainfed and irrigated treatment had lower variation among rotations. The highest coefficient of determination (R^2) and linear component of multiple linear equation of irrigated condition, evidenced higher adaptability of LM to irrigated than rainfed condition (Figure 3a). Thus, the trend of yearly DM increase in the rotations under irrigation (19.2% higher than rainfed) was mainly linked to irrigation treatment whose agronomic effect favoured plant development (Figure 3a). The reduction of DM across the harvests resulted in a significant decrease favoured by plant development whose decline was higher under rainfed (second harvest) than irrigated condition (VI harvest) (Figure 3b). The effect of irrigation on LM rotations favours physiological mechanisms able to reduce summer stasis of vegetative growth, enlarging the period of crop utilization, number of harvests and hence yearly DM production (Figure 3b). The mean differences (value of harvest I minus those of VI) between LM rotations for DM amount to 1.77 t ha^{-1} (Figure 3b). The linear decline evidenced by multi linear regression and R^2 (7.11-0.87X+0.12.1X^2; R^2=0.85**) of DM through the harvests was due to plant senescence during the vegetative cycle which reduced plant height (8.7 cm), stem density (90 stems m^{-2}), and increased the leaf: stem ratio (7.1%) (*data not shown*).

The beneficial effect of irrigation on both LM and BM crops favours plant development and lowered values of WUE in LM and BM (18.9% in LM and 21.1% in BM over mean rotation) (Table 7). The reduced values of WUE in 2-yr and 3-yr meadow and mixture rotations under both irrigated conditions in comparison to those of 1-yr (9.4% and 4.7% in LM and 6.4% and 5.3% BM under rainfed and 16.2% and 17.6% in LM and 25.9% and 7.7% BM under irrigated, respectively) was due to the effect of rotation on OM soil parameter (Table 7). The lower WUE values of LM rotations than those of BM was due to reduced edaphic adaptability to vegetative stasis which conferred longer periods of agronomic exploitation than BM (3 harvests in mixture instead 6 in meadow) (Figure 2b and Figure 3b).

Effect of wheat forage crop rotations on topsoil organic matter

The OM of CDW, DWLM and DWBM rotations under irrigated condition showed regression values of linear and quadratic components lower than those of rainfed (16.0% and 21.7%, respectively) (Figure 4a). The CDW rotation reduced, over a period of 18 years, the initial content (25.1 g kg^{-1}) of OM by 5.9 and 7.6 g kg^{-1} under rainfed and irrigated conditions, respectively (Figure 4a). The mean of OM recorded at the end of the experiment in DWLM and DWBM rotations (25.4 and 22.9 g kg^{-1} under rainfed and 22.1 and 21.6 g kg^{-1} under irrigated, respectively) was reduced in comparison to the content of the beginning trail (Figure 4a). The OM content under rainfed, at the end of the experiment, in comparison to those of the starting, was 2.3 and 0.3 g kg^{-1} higher in 1-yr and 2-yr DWLM and 0.5 g kg^{-1} in 1-yr DWBM and lower in the other rotations (1.5 g kg^{-1} in 3-yr DWLM and 1.7 and 4.6 g kg^{-1}in 2-yr and 3yr DWLM, respectively) (Figure 4a) while under irrigated condition the mean of OM in the DWLM and DWBM rotations was further stressed [lower 3.0 g kg^{-1} (mean DWLM) and 3.5 g kg^{-1} (mean DWBM) than the beginning value, respectively] (Figure 4a).

The OM content of the 1-yr rotation was 7.2% and 13.8% higher in DWLM and 8.6% and 24.2% in DWBM than 2-yr and 3-yr rotations, respectively. A similar trend was observed among the rotations of DWLM and DWBM irrigated conditions (Figure 4a). The multiple regression linear analyses of the trait OM, in the LM and BM rotations under both irrigated treatments, assessed by linear and quadratic components response of rainfed rotations was higher (3.6% and 4.1%, respectively) than those of irrigated (Figure 4b).

The low variation observed among the yearly DM in the harvests of LM and BM crops, in 1-yr, 2-yr and 3-yr LM and BM rotations (Figure 2a and Figure 3a) under rainfed and irrigated treatments evidenced a reduced effect of rotations of both LM and BM crops on DM production. However, the DM increase, recorded under irrigated over rainfed condition (5.03 *vs* 6.15 t ha^{-1} in mixture and 5.53 *vs* 16.99 t ha^{-1}in meadow, respectively), was ascribed to edaphic adaptability existing between BM and LM crops which increased the period of agronomic utilization with consequent hence DM production (Figure 2 a,b and Figure 3 a,b). Thus, the 1-yr, 2-yr and 3-yr of continuous LM and BM rotations under rainfed and irrigated treatments evidenced a reduced effect on DM production of crops and increased OM in the soil (OM content of 3-yr rotation under rainfed and irrigated condition was higher 6.3% and 5.0% in LM and 2.1% and 13.7% in BM than those of 1-yr, respectively). The agronomic advantage of OM left in topsoil from of 3-yr continuous LM and BM rotations increased SY and content of CP in the kernel under both irrigated conditions in the 1-yr DWLM and DWBM than the 2-yr and 3-yr DWLM and DWB rotations (Figure 1a,b). However, the agronomic benefits attained by forage crops on DWLM and DWBM rotations expired its effect after 3-yr in DWLM and DWBM rotations whose content in OM was retained by Adler (2005), Hogg *et al*. (2008) and Martiniello (2011), the threshold for maintain soil fertility for preserving the dynamics of chemical elements in the topsoil. Thus, the DWLM and DWBM crop rotations adopted in the experiments may constitute farming cropping system approaches able to recover the turnover content of OM in the topsoil and sustain the performance of SY and kernel CP content in a Mediterranean environment.

Discussion

Durum wheat forage crops rotation

The largest values of linear component responses of the multiple linear regression evidenced that the variability existing among DW traits was mainly due to DWLM and DWBM rotations rather than irrigation treatments and weather factors (Figure 1).

The ANOVA statistical significant of main factors, in all traits of DW, revealed rotation treatments extremely influenced by agronomic management rather than weather condition (Table 4). However, the lack of some interaction factors in SY and in seed yield components and qualitative traits (*e.g.*, stem m^{-2}, seed spike^{-1}, harvest index and CP) was due to lack of the agronomic effect among experimental main factors which influenced adaptability and crop development in the environment (*data not shown*).

The effect of irrigation reduced the impact of weather on crop physiologic processes, leading to higher WUE than rainfed conditions (Table 7). According to García del Moral and Rharrabti (2007), the reduced variation existing among the WUE in CDW, DWLM and DWBM rotations, in DM of stem instead those of SY stem trait, was caused by environmental changes during the physiological partitioning process of stored compounds in the grain and those in the stems organs of plant (Table 7). The higher WUE in CDW for DM and SY stem traits rather than DWLM and DWBM under rainfed and irrigation treatments (9.4% and 5.0% in rainfed and 18.0% and 33.6% in irrigated conditions for DM and SY stem, respectively) was due to the benefits of LM and BM crop rotations left in the topsoil (Figure 4b) (Pagliai *et al*., 2004; De Vita *et al*., 2007). However, the higher WUE of the DWLM and DWBM rotations under irrigated rather than rainfed was due to the delayed of the vegetative cycle caused by irrigation which favour longer period of transpiration (on average 12 days) before threshing (Table 7) (Rinaldi and Ubaldo, 2007; Cui *et al*., 2009).

The variation of SY across wheat rotation treatments (CDW, DWLM and DWBM) under rainfed and irrigation treatments was due to the effect of agronomic factors on seed yield component traits. Among them, the effect of irrigation on DWLM and DWBM rotation treatments was mainly evident on the trait 1000 seed weight (*data not shown*). The different pattern of CP in seed, of CDW, 1-yr, 2-yr and 3-yr of DWLM and DWBM rotations under rainfed and irrigated conditions, revealed that the physiological process of CP relocation to kernel was related to weather condition, agronomic management and OM content in the topsoil (Figure 1b) (Reeves, 1997; Pagliai *et al*., 2004; De Vita *et al*., 2007; García del Moral and Rharrabti, 2007).

The lower b and S^2d values, found by regression analysis (Eberhart and Russell, 1966), of 1-yr DWLM and DWBM rotations under irrigated than those of rainfed (30.8 and 33.8% in b and 13.1 and 31.2% in S^2d in 1-yr DWLM and DWBM, respectively) was due to the effect of agronomic rotations and irrigation treatments which buffered environmental constraints during wheat crop development. However, the benefit of 1-yr DWLM and DWBM rotations was reduced in 2-yr and 3-yr DWLM and DWBM. The better SY performance of DWLM and DWBM rotations than those of CDW, was achieved by the increase of OM in topsoil, which enhances the agronomic effect of wheat forages rotations (Figure 1a and Figure 4b) (Hudson, 1994; De Vita *et al*., 2007; Martiniello, 2007; Fares *et al*., 2009).

Forage crops

The lack of statistical significance in DM among the two-(HxR and IxR) and three-way (HxIxR) interaction factors in BM rather than LM was due to spring vegetative stasis which reduced the effect of irrigation on crop development (Figure 2a and Figure 3a; Table 4). Therefore, the autumn winter vegetative habitus of mixture benefits crops growing in months with more favourable weather conditions (low light and temperature requirement) to plant growth than meadow (Martiniello, 1999, 2009).

In BM crop, the lower DM yield in the III harvest than those of the previous, was due to the effect of weather conditions on vegetative stasis which reduced the efficiency of physiological processes of plant development (harvest III was 8.2% higher and 20.6% lower than harvests I and II, respectively) (Figure 2b). The reduced number of harvests of BM, in comparison to those of LM, was due to lack of adaptability to weather effects which favour summer vegetative stasis of BM and plant development in LM (Figure 2b and Figure 3b) (Martiniello and Teixteira da Silva, 2011).

The reduced values of WUE in 2-yr and 3-yr LM and BM rotations in comparison to those of 1-yr depend to the effect of rotation on chemical soil parameters (Reeves, 1997; Pagliai *et al*., 2004). However, the lower WUE values of LM rotations than those of BM was consequences of different edaphic adaptability of the crops to weather conditions which reduced the sensibility to vegetative stasis, allowing physiological characteristics able to better exploit the agronomic effect of irrigation treatment. According to Martiniello and Teixeira da Silva (2011), irrigation reduced the effect of weather stress on the physiological development of forage crops, leading to higher WUE than rainfed (mean over rotation treatments of LM and BM: 84 and 90 [L water (kg DM)$^{-1}$] under rainfed and 66 and 73 L [L water (kg DM)$^{-1}$] under irrigated treatment, respectively) (Table 7). Furthermore, the adaptability of LM to develop in summer months conferred longer periods of agronomic exploitation than BM (3 harvests in BM and 6 in BM) allowing greater gap between rainfed and irrigated condition in DM production (5.03 *vs* 6.15 t ha^{-1} in BM and 5.53 *vs* 16.99 t ha^{-1} in meadow, respectively) (Figure 2b and 3b).

Effect of wheat forage crop rotations on topsoil organic matter

The most important agronomic benefits of DWLM and DWBM forage crop rotations was the effect of cultivation on chemical characteristics of topsoil and sustainability of crop in farm cropping systems (Errebhi *et al*., 2004; Shahriar, 2009; Tilman *et al*., 2009). The content of OM in the DWLM and DWBM rotations at the end of the experiment, in comparison to the OM content of CDW, were reduced (lower 0.6 and 1.1 g kg^{-1} under rainfed and 1.7 and 3.1 g kg^{-1} under irrigation, respectively than the content at the beginning of experiment) (Figure 4b).

The OM reduction in DWLM and DWBM under irrigated rotations (mean of 1-yr, 2-yr and 3-yr), as postulated by Hudson (1994), Reeves (1997) and Martiniello (2007), was due to microbial activity for sustaining the higher SY of wheat rotations under irrigated treatment (21.3% and 31.5% in DWLM and DWBM, respectively) (Figure 1a and Figure 4a). Thus, the lower content in OM in 3-yr DWLM and 3-yr DWBM than in other rotations of rainfed and irrigated treatments was due to mineralization of OM for providing nutrient cycling for plant growth (Garrido-Lestache *et al*., 2004; Pagliai *et al*., 2004; De Vita *et al*., 2007; Tilman *et al*., 2009) (Figure 1a).

The LM and BM rotations increased the content of OM in topsoil favouring the mineralization process for production of nutrient cycling for sustaining wheat forage crops rotations (Figure 1a and Figure 4b) (Cui *et al*., 2009; Tilman *et al*., 2009). The irrigation combined with rotation treatments increased OM in LM and BM rotations favouring plant development and WUE when compared with rainfed regime (L (kg DM)$^{-1}$ was 73 and 91 in BM and 66 and 81 in LM under irrigated and rainfed, respectively) (Table 7). The benefit of LM and BM rotations was due to leaving of biochemical compounds left in the soil which increase the source of OM for mineralization process for satisfying the demand of nutrients for supporting the higher SY of DWLM and

DWBM rotations under irrigated than those under rainfed (Figure 1a and Figure 4a) (Reeves, 1997; Kumar and Goh, 2000; Martiniello, 2007; Pala *et al*., 2007). Thus, cropping systems based on alternation of three years of continuous DW rotations with as many years of LM and BM crop rotations, were able to restore the turnover of OM and sustaining DW and quality of crop production in environments with Mediterranean climate (Figure 1a and Figure 4b). However, the agronomic advantages conferred by 3 years of continuous LM and BM rotations in both irrigated conditions expiring their agronomic effects after 3-yr DWLM and 3-yr DWBM rotation (Figure 1a and Figure 4a). The 3-yr DWLM and DWBM rotation stressed the OM content favouring, as postulated by Adler (2005), Hogg *et al*. (2008) and Martiniello (2011), the reduction of soil physiological activity for maintaining conservation soil fertility and dynamics of mineral elements for recycling nutrients for plant development.

Conclusions

The cropping system used in the study is an agronomic approach for developing sustainable agriculture in environments with a Mediterranean-type climate. Three year continuous LM and BM forage crop rotations favour the turnover of OM content in the topsoil and increase SY, CP of kernel and ensure yield stability of DW crop. The agronomic effect of LM and BM crops on DWLM and DWBM rotations exhausts its benefits after three years of continuous DW rotations. Irrigation rather than rainfed treatment reduced the impact of weather conditions, improving WUE, SY and stability of DW production. Furthermore, irrigation combined with 3-yr DWLM and DWBM cropping rotations weakened the content of OM at the starting of experiment by 0.17 g y^{-1} in the DWLM and 0.19 g y^{-1} DWBM against 0.42 g yr^{-1} of CDW rotations. The gap of OM content at starting and at the end of experiment in the DW, DWLM and DWBM rotations under rainfed not occurred in DWLM, faint in DWBM (0.08 g y^{-1}) and consistent in CDW (0.33 g y^{-1}).

The evolution trend of OM content, particularly under favourable weather conditions, across wheat forage cropping system evidenced that the crop rotations plan used was suitable to favour the turnover of OM in the topsoil and to sustain the performance of SY and CP of wheat production in Mediterranean-type environments.

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