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Effects of crop residue management on winter durum wheat productivity in a long term experiment in Southern Italy

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ABSTRACT

A long-term experiment comparing different crop residue (CR) managements was established in 1977 in Foggia (Apulia region, southern Italy). The objective of this study was to investigate the long-term effects of different types of crop residue management on main yield response parameters in a continuous cropping system of winter durum wheat. In order to correctly interpret the results, models accounting for spatial error autocorrelation were used and compared with ordinary least square models.

Eight crop residue management treatments, based on burning of wheat straw and stubble or their incorporation with or without N fertilization and irrigation, were compared. The experimental design was a complete randomized block with five replicates.

Results indicated that the dynamics of yield, grain protein content and hectolitric weight of winter durum wheat did not show any decline as usually expected when a monoculture is carried out for a long time. In addition, the temporal variability of productivity was more affected by meteorological factors, such as air temperature and rainfall, than CR management treatments. Higher wheat grain yields and hectolitric weights quite frequently occurred after burning of wheat straw compared with straw incorporation without nitrogen fertilization and autumn irrigation and this was attributed to temporary mineral N immobilization in the soil. The rate of 50 kg ha^{-1} of N seemed to counterbalance this negative effect when good condition of soil moisture occurred in the autumn period, so yielding the same productive level of straw burning treatment.

1. Introduction

Winter durum wheat (*Triticum durum*, Desf.) is the main cereal crop in Italy with more than 1.25 Mha cultivated in 2013 and with mean yield of 3.2 t ha^{-1}. Almost 70% of the cultivation is concentrated in southern Italy, where meteorological factors, such as rainfall and air temperature during the growing season, strongly influence crop yield. In the past continuous wheat and two-year wheat-fallow rotation have been the cropping systems extensively used in rainfed farming systems. Recently, as in the district of Foggia (in the northern part of Apulia region), durum wheat is frequently rotated with tomato in two- or three-year rotations (two years of winter wheat and one of tomato) and/or with irrigated and profitable catch crops such as cabbage.

Traditional agronomic practices involve the use of moldboard plowing as primary tillage, followed by repeated secondary shallow tillage. With the main plowing, straw and stubble, after being chopped, are buried into the soil or, alternatively, are burned in early September before carrying out soil tillage.

Stubble and straw burning is a common practice in areas where cereals are traditionally cultivated and it ensures quick seedbed preparation and residue clearance without machinery utilization. Moreover, burning is mainly performed in areas characterized by irregularity or steepness of land or where there is less need for straw due to reduction in heads of cattle. On the other hand, it can also be considered as a cheap way to limit the spread of several pathogens present in the residues of the previous crop and to reduce the number of germinable weed seeds. However, this practice has been prohibited by law owing to several drawbacks in many countries including Italy, even though in some Italian regions it is allowed, but in narrow time windows and with agronomic practice such

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as “precesa”. It consists of buffer strips of at least 10 meter wide, along the field border cultivated with cereals, which are prepared immediately after harvest.

In several studies crop residue (CR) burning has been reported as beneficial for yield increase, but it should be avoided since it reduces organic matter input in the soil with consequent negative effects on environment and soil quality (Limon-Ortega et al., 2009). In fact according to these studies, burning reduces the amount of organic matter incorporated in soil, soil organic carbon and carbon substrates for soil microorganisms (Hamman et al., 2007). This causes a dramatic reduction in microbial biomass, number of bacteria and basal respiration (Glaser et al., 2002), so affecting CO_2 and N emissions from soil.

A number of studies has demonstrated that burning residues over a period of twenty years did not result in any significant reduction in grain yield or soil organic matter; a reduction in microbic activity was then noted with increase of the loss of soil organic carbon (Rasmussen and Collins, 1991). Straw and stubble burning does not determine rapid loss of soil carbon but significantly affects important physical properties, such as soil colour, aggregate stability and water infiltration rate (Rasmussen et al., 1980).

As reported in the exhaustive review by Kumar and Goh (2000), several scientists have examined the effect of CR management on yield of the following crop; however, the results from these experiments are conflicting because of a number of factors involved, such as residue quality, edaphic factors, health status of the previous crop, and their interactions with management practices.

Kumar and Goh (2000) assert that “under conditions of optimum fertility, adequate soil water supply and absence of pests and diseases, grain yields are largely unaffected by management ” whereas pollution and sustainability are the major concerns.

Under environmentally constrained conditions, CR management practices may affect grain yield trends significantly. For example, under low soil moisture conditions no-tillage and surface mulch treatment provided higher crop yields because of greater water conservation and evaporation reduction (Hatfield and Prueger, 1996; Prihar et al., 1996).

Under high soil fertility conditions or where long-term additions of CR have increased the amount of available N, yield generally increases (Tian et al., 1993; Dick and Christ, 1995), especially when crop demand and nutrient availability from residue decomposition are synchronized (Becker and Ladha, 1997).

CR incorporation after harvest might determine lower yields due to microbial N immobilization compared to fields where the residues are burned or removed (Limon-Ortega et al., 2000). It implies the need to apply higher N rates to compensate crop for a potential N deficiency and maintain constant yield levels. However, the efficiency of this action depends also on the date, rate and type of N fertilizer.

In a recent detailed literature review, Lehtinen et al. (2014) quantified the effects of CR incorporation on soil organic carbon and greenhouse gas emission across Europe by evaluating to what extent they are influenced by environmental zone, clay content of soil, duration of experiment, experimental setup and kind of CRs. The study indicated that the impact of CR incorporation on soil organic carbon sequestration is positive, but not for CO_2 and N_2O emissions that are expected to increase compared with CR removal. They also showed that long-term CR incorporation may increase crop yields but over a very long term (>20 years) and under continental climate. In fact, the Authors, reporting also the partial results of the long term experiment (LTE) described in this paper and of another similar experiment located at the same farm of Foggia, asserted that the incorporation of CRs lowered yield because of the poor mineralization and strong N immobilization caused by arid climate and low soil N content (Maiorana, 1998).

When a crop is continuously grown, a decrease in yield may be observed. In particular, yield losses in continuous cropping can be attributed to various mechanisms, such as reduction of soil water reservoir and nutrient availability, increase of weed populations, proliferation of certain pathogens, reduced transformation of nutrients owing to lower activity of soil microorganisms. Such processes can have significant impact on nutrient and water use efficiency (Nielsen et al., 2002; among others).

Several studies reported by Lithourgidis et al. (2006) showed yield reduction after continuous wheat cropping. Wheat grain yields were decreased considerably in the third year of continuous cropping in Iran, due to the adverse effects of continuous cropping and weeds (Bahrani et al., 2002). Twenty-five years of continuous wheat cultivated in India reduced wheat grain yields to almost zero (Sharma and Subehia, 2003).

On the other hand, other studies have shown that continuous cropping can be carried out in cereal production without significant yield losses. Jones and Singh (2000) found that in the medium term continuous barley cultivation was a sustainable cropping system provided that adequate annual fertilization was maintained. Procházková et al. (2003) found that wheat yield was not affected significantly by continuous cropping.

In evaluating the effect of different cropping systems on yield response, statistical analysis plays a crucial role. To assess long-term effects of agronomic management on yield response parameters, ordinary least squares (OLS) regression models are commonly employed. Their use requires assumptions of normality, independence and homoscedasticity of residuals. However, residuals are often spatially correlated (Lark, 2000; Kissling and Carl, 2007) and, if the test statistic does not account for spatial dependence it will be too large and consequently type I error, i.e. the incorrect rejection of the null hypothesis, will tend to increase (Rodrigues et al., 2013; Schabenberger and Gotway, 2005). Failure to account for spatial dependence can then result in erroneous conclusions (Littell et al., 2006) and lead to critical misinterpretation errors and improper management decisions.

Linear mixed effect models (LME) allow spatial correlation components to be assessed and filtered from the total residual term of the model so improving the protection of statistical tests (Rodrigues et al., 2013). Some studies have pointed out that mixed effects models, which incorporate spatial variability, can improve the understanding of factors affecting crop yield and plant response, and are then crucial in ecological and environmental studies (Lambert et al., 2004; Rodrigues et al., 2013; Kissling and Carl, 2007).

A long-term experiment, comparing different CR managements, was established in 1977 in Foggia (Apulia region, southern Italy) and is still ongoing. The objective of this study is to investigate the long-term effects of different types of CR management on the main yield response parameters in a continuous cropping system of winter durum wheat. In order to correctly interpret the results, models accounting for spatial error autocorrelation were used and compared with ordinary least square models.

2. Material and methods

2.1. Experimental layout and agronomic practices

The field experiment was established in 1977 at the experimental farm “Podere 124” of CRA-SCA located in Foggia (41°27′ latitude N, 15°36′ longitude E, 90 m above sea level) on a soil with clay-loam texture of alluvial origin, classified by Soil Taxonomy-USDA as fine, mesic, Typic Chromoxerert (Soil Survey Staff, 1992). The soil has a good availability of total nitrogen ($0.12\ g\ 100\ g^{-1}$) and organic matter ($2.07\ g\ 100\ g^{-1}$) and a content of 41 of available phospho-

Table 1
Synthetic description of treatments of crop residue (CR) management and applied coefficients of orthogonal contrasts.

Treatment	Description of CR management	C1	C2	C3	C4	C5	C6	C7
T1	Burning	7	0	0	0	0	0	0
T2	Incorporation (Inc), No nitrogen (N) and water (W)	−1	6	0	0	0	0	0
T3	Inc, 50 kg N ha^{-1}, no W	−1	−1	1	1	1	0	0
T4	Inc, 100 kg N ha^{-1}, no W	−1	−1	1	0	−2	0	0
T5	Inc, 150 kg N ha^{-1}, no W	−1	−1	1	−1	1	0	0
T6	Inc, 50 kg N ha^{-1}, 50 mm W	−1	−1	−1	0	0	1	1
T7	Inc, 100 kg N ha^{-1}, 50 mm W	−1	−1	−1	0	0	0	−2
T8	Inc, 150 kg N ha^{-1}, 50 mm W	−1	−1	−1	0	0	−1	1

Table 2
Likelihood ratio test to compare spatial and non-spatial models for grain yield, thousand seed weight (TSW), grain protein content (GPC) and hectolitric weight (HTW).

Variable	Model	−2 res log	Log likelihood ratio test (χ^2)	df	*P* value
Yield	Spatial	1417.6	59.2	2	<0.0001
	Non spatial	1476.8			
TSW	Spatial	4798.3	19.7	2	<0.0001
	Non spatial	4818			
GPC	Spatial	2679.1	37.9	2	<0.0001
	Non spatial	2717			
HTW	Spatial	3680	97.1	2	<0.0001
	Non spatial	3777.1			

Table 3
F value and probability level, within the parenthesis, for each fixed effect corresponding to spatial and non-spatial models for grain yield, thousand seed weight (TSW), grain protein content (GPC) and hectolitric weight (HTW).

Variable	Model	Treatment (*T*)	Year (*Y*)	*Y* × *T*
Yield	Spatial	27.81 (<0.0001)	442.8 (0.0376)	3.21 (<0.0001)
	Non spatial	32.95 (<0.0001)	503.07 (<0.0001)	3.06 (<0.0001)
TSW	Spatial	30.03 (<0.0001)	424.77 (0.0384)	2.34 (<0.0001)
	Non spatial	35.10 (<0.0001)	426.52 (<0.0001)	2.29 (<0.0001)
GPC	Spatial	40.01 (<0.0001)	77.69 (<0.0001)	2.11 (<0.0001)
	Non spatial	75.50 (<0.0001)	84.30 (<0.0001)	1.95 (<0.0001)
HTW	Spatial	41.43 (<0.0001)	522.11 (0.0347)	2.92 (<0.0001)
	Non spatial	48.03 (<0.0001)	502.96 (<0.0001)	2.57 (<0.0001)

rus (P_2O_5). In summer it very frequently shows 4–5 cm wide cracks from the surface to 50-cm depth.

The climate is classified as "accentuated thermomediterranean" (Unesco-FAO classification), with temperatures that may fall below 0 °C in winter and exceed 40 °C in summer. Rainfall is unevenly distributed throughout the year and is mostly concentrated in the winter months with a long-term annual average of 550 mm.

The experimental farm is located in Apulian Tavoliere, a very important area, from agricultural and economic point of view, mostly cropped with winter durum wheat (*T. durum*, Desf.).

The experimental design is a randomized block with five replicates, unit plots of 80-m^2 size and eight crop residue (CR) management treatments as follows: T1, burning of crop residues; T2, incorporation of stubble and straw (CR) into the soil; T3, CR incorporation + 50 kg ha^{-1} of N (as urea) spread on CR before the incorporation; T4, CR incorporation + 100 kg ha^{-1} of N spread on CR; T5, CR incorporation + 150 kg ha^{-1} of N spread on CR; T6, as T3 treatment + 500 m^3 ha^{-1} of water on CR; T7, as T4 treatment + 500 m^3 ha^{-1} of water on CR; T8, as T5 treatment + 500 m^3 ha^{-1} of water on CR. The minimum doses of nitrogen added to the residues (as urea) were determined taking into account that soil micro-organisms (fundamental to decomposition of CR) require a quantity of N between 0.8 and 1.4 kg per 100 kg of dry matter incorporated; the amount of water used was established considering a rainfall of 50 mm. In all treatments, 100 kg ha^{-1} of P_2O_5 was applied before the main tillage as well as 100 kg ha^{-1} of N as top dressing (NH_4NO_3).

After wheat harvesting, typically occurring in the middle of June, straw and stubble are chopped to 10–15 cm lengths and spread back on the plots of the treatments from T2 to T8. The urea is then applied and next incorporated with the chopped straw and stubble into the soil through the primary ploughing of 40 cm. In accordance with local practices, the secondary tillage consists of tooth-harrow or disc-harrow for seedbed preparation in order to improve wheat germination. The sowing is usually carried out in October or November but it may be delayed to December due to adverse meteorological conditions. Durum wheat is sown in all plots on the same day with a conventional sowing machine at rows 15 cm apart and 3–4 cm deep. During the research period, 1977–2012, different cultivars were sown with cycles of 5 years: Valgerardo (sown between 1977 and 1981), Appulo (1982–1986), Latino (1987–1991), Appio (1992–1995), Simeto (1996–1999 and 2006–2012), Ofanto (2000–2005). Due to the particularly dry conditions, supplemental irrigations were done in eight years during the entire experiment with irrigation depths ranging from 30 to 70 mm and mostly from January to April.

Weeds are controlled chemically with herbicides applied in March before stem elongation and in accordance to the local practices.

At winter wheat harvesting, grain production is measured on the whole area of each plot. Grain samples are randomly collected at ten points of each plot for determining grain dry weight (obtained by drying composite samples until constant weight), and total N content (Fisons CHN elemental analyser, model EA 1108). After drying, seeds of each sample are separated and weighed for calculating 1000-kernel weight (g). Hectolitric weight (weight per unit volume) was measured on three samples of 250 g per plot and expressed as kg hl^{-1}, using a "FOSS INFRATEC 1241" grain analyser equipped with test weight module.

2.2. Statistical analysis

2.2.1. Preliminary statistical analysis for wheat yield response parameters

Descriptive statistics were calculated to synthesize main features of data distribution for the grain yield and quality parameters under study: grain protein content (GPC), hectolitric weight (HTW) and thousand seed weight (TSW). In addition the variables were tested for heteroscedasticity by cultivar and treatment classes with Levene's test.

2.2.2. Linear mixed effect model

The standard linear model (OLS) can be written as:

$$Y_i = \sum\nolimits_j^p x_{ij}\beta_j + e_i \qquad i = 1, \ldots N$$

where y_i are N data points of the response variable (i.e., wheat yield) at location i, x_{ij} are the observations of the p explanatory variables (j), which can be continuous or dummy variables, declaring class membership of a categorical variable (i.e., treatment, cultivar), $(\beta_i) \ldots (\beta_p)$ are fixed effect coefficients to be estimated, and e_i are unknown independent and identically distributed normal random variables with mean 0 and variance σ^2.

The previous equation can be written using matrix notation as:

$$\mathrm{Y} = \mathrm{X}\beta + \mathrm{e}$$

where ***Y*** is the vector of the responses, ***X*** the matrix of the observations, $\boldsymbol{\beta}$ the vector of the unknown fixed effect coefficients and **e** the vector of independent and identically distributed normal random errors, or in symbol, $e \sim N(0, \sigma^2 \boldsymbol{I})$ where $\boldsymbol{I}$ is identity matrix (Rodrigues et al., 2013). If the error variance σ^2 is not constant but varies with the classes of a categorical variable (i.e. year, cultivar), the model is heteroscedastic.

However, independence assumption about $\boldsymbol{Y}$ is often too restrictive and linear mixed effect model extends the general linear model by allowing elements of $\boldsymbol{Y}$ to be correlated on both space and time. This can be performed in the following way:

(i) through specification of a spatial covariance function of $\boldsymbol{e}$ as a function of the distance between two locations i and j (d_{ij}), say: $e \sim N(0, \boldsymbol{R})$, for spatial variability;

(ii) and the addition of a random effect in the model ($\mathbf{Zu}$), where $\boldsymbol{u} \sim N(0, \boldsymbol{G})$. $\boldsymbol{Z}$ is a matrix, similar to $\boldsymbol{X}$, that captures the complex covariance structure of the temporal factor. Differently from $\boldsymbol{\beta}$, the vector $\boldsymbol{u}$ does not contain parameters but random variables.

The general linear mixed effect model can thus be written as:

$$\mathbf{Y} = \mathbf{X}\beta + \mathbf{Zu} + \mathbf{e}$$

with Cov $[\boldsymbol{u}, \boldsymbol{e}] = 0$, which implies the assumption that $\mathbf{u}$ and $\mathbf{e}$ are uncorrelated.

In the spatial model, $\boldsymbol{R} = \sigma^2{}_p \boldsymbol{F} + \sigma^2{}_1 \boldsymbol{I}$, where $\boldsymbol{F}$ is an $N \times N$ matrix whose ijth element is $f(d_{ij})$; thus, the error variance of the OLS model ($\sigma^2 \boldsymbol{I}$) is split into a spatially structured ($\sigma^2{}_p \boldsymbol{F}$) variance and a spatially independent (residual) variance ($\sigma^2{}_1 \boldsymbol{I}$).

The spatial covariance model has the form:

$$\mathrm{Var}[e_i] = \sigma^2{}_p + \sigma^2{}_1$$

$$\mathrm{Cov}[e_i, e_j] = \sigma^2{}_p [f(d_{ij})],$$

where $f(d_{ij})$ is the selected geostatistical spatial covariance function of the distance d_{ij} between pairs of observations (i, j), using a parameter ρ for spatial scale (range); $\sigma^2{}_1$ and $\sigma^2{}_p$ correspond to the geostatistical parameters of nugget effect and partial sill, respectively. The spatial covariance was modeled using a spherical function of the distance.

A further complexity was added in the spatial model by allowing variance to vary as a function of cultivar, because it can cause heterogeneity in the spatial covariance function. Specifically, two groups were defined that included most productive (Simeto, Ofanto; class A) and less productive (Appio, Appulo, Latino, Valgerardo; class B) cultivars; different spatial models were thus fitted per cultivar class.

The fitting process relies on an iterative procedure aimed at maximizing the log likelihood of the residuals using restricted maximum likelihood method (REML; Littell et al., 2006). The fixed effects estimates are obtained as generalized least squares estimates evaluated at the REML estimates of the covariance parameters.

The temporal relationship was explored by postulating homoscedastic autoregressive structure of order 1 (AR(1)) for the matrix $\boldsymbol{G}$, with correlations that decline exponentially with the time series (Rodrigues et al., 2013). The AR(1) covariance structure has two unknown parameters: the variance ($\sigma^2{}_t$) and the lag-one correlation (ρ_t). The year, as temporal factor, was included in the model also as a fixed effect, as a dummy variable in the matrix $\boldsymbol{X}$, in order to assess systematic or trend component in crop parameters variation.

The fixed effects of the model were then: treatment, year, the interaction between year and treatment, and cultivar.

Non-spatial models (OLS), including the same fixed effects of the spatial models but with $F = 0$, were also computed.

In this study, to test the impact of the types of CR management on wheat yield, different regression models were estimated and compared: ordinary least squares (OLS) models and linear mixed effects (LME) models with residual autocorrelation and heteroscedasticity (Schabenberger and Gotway, 2005).

2.2.3. Comparison of spatial and non-spatial models

Spatial and non-spatial models were compared using likelihood ratio statistic (Castrignanò et al., 2005). The test compares two covariance models, one as a special case of the other. Specifically, it tests whether the simplifications used in the non-spatial model are still applicable in the experimental conditions (Wolfinger, 1993). Under the null hypothesis that the spatial model is not different from the non-spatial model, the likelihood ratio statistics is distributed as χ^2 with the number of degrees of freedom equal to the difference in the number of parameters between the two models. Because the fixed part is the same in the spatial and non-spatial models compared, only the parameters in the variance–covariance structure need to be considered, and thus the test is computed under the null hypothesis H0: $\rho = 0$ and $\sigma_p^2 = 0$, when (F) reduces to (I), with two degrees of freedom.

When the test is not significant, the most parsimonious model is selected and evaluated through residual analysis (mean and standard deviation of standardized error which should be close to 0 and 1, respectively).

All statistical analyses were computed using SAS/STAT (release 9.3, SAS INSTITUTE) and the models were estimated using PROC MIXED. Least Square (LS) means and contrast statements were used to evaluate the differences among the treatments. Table 1 shows the coefficients of the seven orthogonal contrasts (C1–C7).

3. Results

3.1. Temperature and precipitation trends

Rainfall for the whole cropping cycle (September–June) varied considerably throughout the 36-year experimental period ranging from 244 mm in 1988/1989 to 692 mm in 1979/1980 with 25th, 50th and 75th percentile values of 357, 422 and 485 mm, respectively. Nearly 70% of the annual rainfall fell during the period between September and February and the remaining 30% between March and May. Precipitation and water deficits were characterized by similar behaviour remaining almost constant during the course of experiment, although the frequency of wet years seems to increase in the recent period with four years out of six having annual values above the 75th percentile (Fig. 1). No particular trend was detected for minimum and maximum temperature (data not shown).

1.2 Preliminary statistical analysis for wheat yield response parameters

Descriptive statistics for the variables under study were computed. The overall coefficients of skewness and kurtosis were close to zero, indicating no substantial departure from normal distribution; for this reason normality for all variables was assumed.

Results of Levene's test indicated that variance was homogeneous over treatment groups for all the variables; heteroscedasticity was instead observed for cultivar group with exception of TSW (Table A.1).

3.2. Linear mixed effect models analysis

Results of residual analyses confirmed the goodness of fitting since: residuals had a mean close to 0 (−0.047 for yield; 0.617 for TSW; 0.008 for protein content; −0.16 for HTW); the histograms of residuals (data not shown) showed a bell shaped distribution; the (q–q) plots of sample versus theoretical quantiles of the four variables fitted to the 1:1 line quite well, with the exception of a few low and high values especially for grain yield.

The stochastic effect of the temporal factor was not significant because the covariance function parameters were not significantly different from zero. Therefore, the temporal factor was excluded

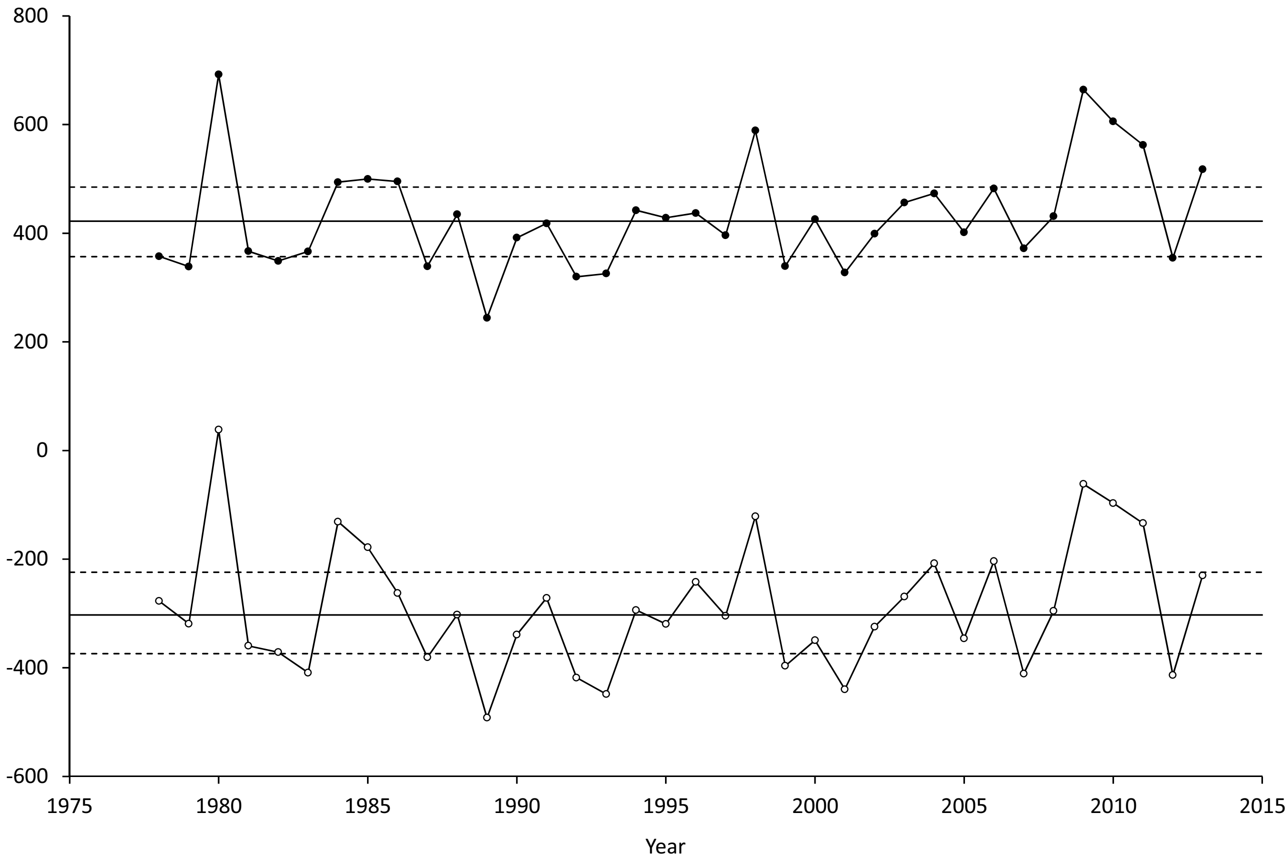

Fig. 1. Seasonal rainfall (dot) and water deficit (circle), calculated as "Rainfall—Reference evapotranspiration", from September 1st to May 31th during the 36 years of the research. The continuous lines represent the median values, the dashed lines represent the 25th and 75th percentiles.

from the model as a stochastic effect. Spatial covariance structure was significant for all variables as a result of the high significance of the log-likelihood ratio test (Table 2).

In Table A.2, the estimates of the covariance function's parameters of the spatial models for each cultivar group and variable (yield, TSW, GPC, HTW) are reported. For yield, a significant spatial structure was observed for the most productive group (class A), with a significant range estimate (P = 0.0174; Table A.2). The fitted covariance function for the less productive group of cultivars (class B) was instead not significant (Table A.2).

A significant spatial structure for the most productive group of cultivars (class A) was observed also for TSW, with significant partial sill (P = 0.0305) and range (P = 0.0003), but for group B the spatial component was not significant. For GPC both partial sill and range were significant for group A, whereas for group B the spatial component was significant but not spatially structured. No significant spatial structures were observed for HTW.

In any case, the structural component of variation for all variables was only a small (though significant) proportion of the total error variance, most of which was included in the residual. This might depend on the data that were averaged on the plot, with the consequent loss of information on within-plot variation and the lack of spatial continuity.

The above results seem to indicate that the varieties differ from a structural point of view. More specifically, the more recently introduced cultivars (Simeto and Ofanto), besides being more productive, seem to show a quite conservative spatial structure over time, whereas class B cultivars are characterized by larger variability, mostly of erratic type.

The range estimates were much shorter for TSW and GPC than for yield (Table A.2). This is indicative that the processes affecting grain quality work over shorter scales compared with those of production (nitrate absorption by roots and/or leaching).

The fixed effects, treatment, year and their interaction, were significant for all variables and for both spatial and non-spatial models, whereas cultivar was no significant (Table 3). However, it is possible to observe from Table 3 that F values were higher for non-spatial models for main effects (year and treatment), but the tendency was inverted for interaction. Therefore, the use of models taking into account spatial autocorrelation of residuals might be critical to correctly evaluate treatment significance, particularly in the case with fewer observations. Moreover, ignoring spatial dependence might distort the results and increase the possibility of falsely declaring significant effects (i.e., Type I error) (Schabenberger and Gotway, 2005; Kissinlg and Carl, 2007). Conversely, spatial models can disclose, better than non-spatial models, weak interactions between the factors.

3.3. Productive parameters

Table 4 shows the average values of productive parameters examined for the eight crop residue (CR) management treatments. A strong and statistically significant linear relationship between TSW and HTW with R^2 close to 1 was observed (data not shown), therefore we preferred to consider only HTW because it is commonly utilized to assess wheat grain quality together with GPC and other parameters.

3.3.1. Yield

Fig. 2 shows the averaged temporal trend of winter wheat yield that ranged from a minimum value of 0.5 t ha^{-1} recorded in 1980 to 6.4 t ha^{-1} in 2012. Yield showed a significant linear trend

Table 4
Means and standard error (S.E.) of productive parameters (grain yield, grain protein content, GPC and hectolitric weight, HTW) of winter durum wheat submitted to CR management treatments.

Treatment	Grain yield		GPC		HTW	
	$t\ ha^{-1}$		%		$kg\ hl^{-1}$	
	Mean	S.E.	Mean	S.E.	Mean	S.E.
T1	3.35 a	0.068	14.09 e	0.119	78.14 ab	0.249
T2	3.21 b	0.068	14.39 e	0.119	78.40 a	0.249
T3	3.09 c	0.068	15.32 c	0.120	77.48 c	0.245
T4	3.00 d	0.068	15.82 b	0.119	77.02 d	0.249
T5	2.90 e	0.068	16.16 a	0.119	76.67 e	0.248
T6	3.39 a	0.068	14.99 d	0.120	77.92 b	0.250
T7	3.31 a	0.067	15.36 c	0.119	77.49 c	0.247
T8	3.13 bc	0.068	15.57 bc	0.120	77.17 d	0.250
Orthogonal contrast (probability level)						
C1	<0.0001		<0.0001		0.0001	
C2	0.0301		<0.0001		0.0001	
C3	<0.0001		<0.0001		0.0001	
C4	<0.0001		<0.0001		0.0001	
C5	**0.9445**		**0.5236**		**0.6168**	
C6	<0.0001		0.0005		0.0001	
C7	**0.1883**		**0.5908**		**0.6138**	

Treatment means followed by different letter were significantly different (LSmeans test; $P \leq 0.05$). The no-significant contrasts are reported in bold.

($P < 0.0013$) with a slope of 68 $kg\ y^{-1}$ over the course of the experiment. This positive trend may be due to genetic progress that affected the cultivars used in the experiment. However, due to the great temporal variability in crop yield, the agricultural years were classified in three groups of low, medium and high wheat productivity, depending if their yields were lesser than 25th percentile (2.3 $t\ ha^{-1}$), between 25th and 75th (4 $t\ ha^{-1}$) and greater than 75th percentile, respectively.

In comparison to the impact of "year" effect on wheat yield, CR management showed less marked overall changes with the largest differences between the most productive treatment (T6) and the least productive treatment (T5) of only 17%. However, due to the high number of freedom degrees, many of the statistically significant differences detected among the means of the eight treatments have little practical bearing (Table 4).

As regards the orthogonal contrasts, T1 increased yield by 0.2 $t\ ha^{-1}$ compared to the average of the other treatments, but significant differences were also detected as a function of CR incorporation. In particular, T2 slightly increased the yield by 0.08 $t\ ha^{-1}$ compared to average of T3–T8 treatments. Applying 50 mm of water on straw and stubble significantly increased the yield by 0.3 $t\ ha^{-1}$, as indicated by C3 contrast. The results of C4 and C6, that test the linearity among T3–T5 and T6–T8, respectively, showed that increasing the N fertilization rates (from 50 to 150 $kg\ ha^{-1}$) on straw had the effect of linearly reducing the yields with rates of yield decrease of 1.9 and 2.6 kg of yield per kg of added N with no water (T3–T5) and with water (T6–T8), respectively. Furthermore, the tests of C5 and C7 allow you to reject the hypothesis of deviation from linearity.

Considering the combined effect of CR incorporation, nitrogen fertilization and irrigation on straw, the single comparisons showed that T1 and T6 were the most productive treatments with mean yield of 3.4 $t\ ha^{-1}$. In comparison to this productive level, T2 and T3 (i.e., straw incorporation without N and with 50 $kg\ N\ ha^{-1}$, respectively) decreased the yield by 0.15 and 0.28 $t\ ha^{-1}$ (by −4 and −8%), respectively. These results indicated that the spreading of nitrogen on straws may be irrelevant or negative in absence of even small water supply. Therefore, even light rainfalls can facilitate CR decomposition and seedling emergence.

The "year by year" comparisons, within the two treatment groups, "CR incorporation with no-water" (T3, T4 and T5) and "CR incorporation with water" (T6, T7 and T8), confirmed that T3 and T6 were the most productive treatments in each group (Fig. A.1). In fact, T3 or T6 never determined significantly lower yields than those obtained with the other two treatments of the corresponding group. For this reason, hereinafter we will examine the interaction "year × treatment" only for the treatments T1, T2, T3 and T6. Temporal paths of winter wheat yield submitted to these treatments are shown in Fig. A.2 with the years ranked in three groups of low, medium and high productivity, as described before. For the first category, these treatments did not affect significantly the grain yield in 4 out of 9 years (44%) and in the remaining years T6 was the most productive treatment followed by T1 in 4 years and T2 in 3 years. The percentage difference between maximum and minimum annual yields varied from 20 to 30%.

In the medium-productive years, no statistical differences were detected in 5 out of 18 years (33%). T1 and T6 confirmed their positive impact on yield in 8 and 10 years (44 and 55%) respectively, while T2 and T3 were included among the most productive treatments in 5 and 3 years (28 and 17%). In the 13 years where statistical differences were observed, the range between minimum and maximum annual yield was from 10 to 30% with exception of 1980, when the difference reached 43% between the average over T1, T3 and T6 vs T2.

Finally, in the high-productive years, there were no statistical differences in 33 per cent of years and the most productive treatments were T3 (5 years), T1 (4 years), T6 (2 years) and T2 only in 1991. The percentage difference between maximum and minimum annual yields varied from 10 to 20% except for 1991, when the difference was higher than 45%.

To further investigate the interaction between treatment and year of different productivity, the difference in yield between T2 and T3 was evaluated in relation to rainfall occurred in the period from September to November. Fig. 3 shows that T2 determined annual yields higher than T3 until the rainfall of the period considered was less than about 160 mm. With greater values of seasonal rainfall the difference between T3 and T2 tended to increase linearly in favor of treatment that involves N straw fertilization.

3.3.2. Grain Protein content and hectolitric weight

Fig. 2 shows also the dynamics of grain protein content (GPC) and hectolitric weight (HTW). The behaviour of GPC was affected by higher variability until 1998 compared with the following period until 2013 (variation coefficients of 12 and 8%, respectively).

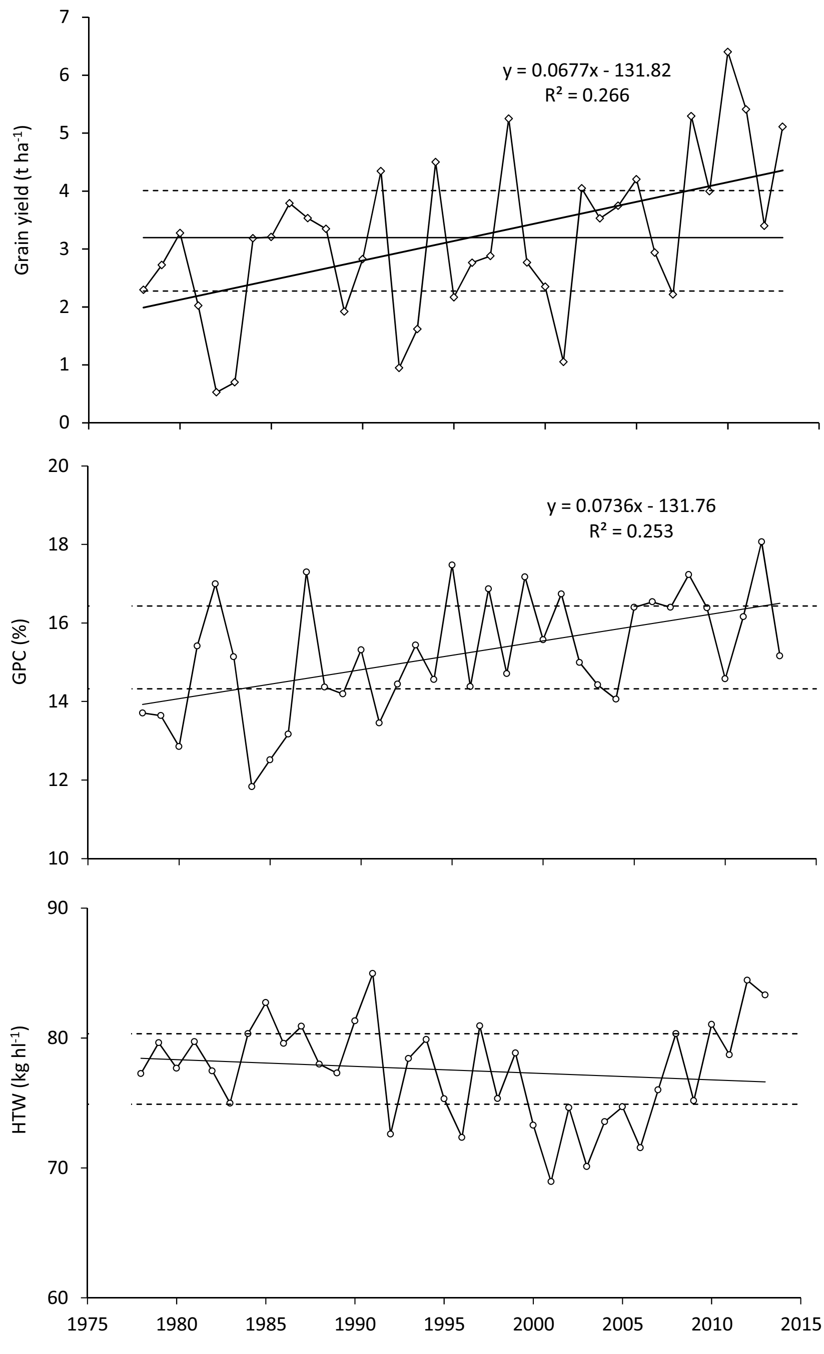

Fig. 2. Average temporal dynamics of grain yield, grain protein content (GPC) and hectolitric weight (HTW) of winter durum wheat. The continuous and dashed orizonthal lines represent the median and the 25th and 75th percentiles, respectively. The linear regressions are also reported with slope, intercept and R^2 statistically significant for $P < 0.05$.

The behaviour of HTW was fairly constant until 1999, and then decreased below the 25th percentile, whereas in the last 13-year period increased linearly up to 84 kg hl^{-1}, as average over the last two years.

The results of statistical analysis, and in particular those of the orthogonal contrasts and paired comparisons, showed that the T1 and T2 decreased GPC by 1.3% compared with the average over the other treatments. The irrigation decreased GPC by 3% on average. According to the orthogonal contrasts C4–C5 and C6–C7, N fertilization increased GPC with a linear response characterized by slopes of 0.008 and 0.006% per kg of added N for T3, T4, T5 (N with no water on straw) and T6, T7, T8 (N with water on straw), respectively.

Conversely, T1 and T2 determined the highest HTW with a mean value of 78.3 kg hl^{-1}. As indicated by C3 contrast, irrigation had a positive effect on HTW causing a slight increase of 0.6%.

HTW responded negatively to N fertilization with a decrease of 0.0075 and 0.0081 kg hl^{-1} per kg N spread with irrigation (T5, T6 and T7) and without irrigation on straws (T3, T4 and T5), respectively.

Similar to yield, the temporal paths of T4, T5, T7 and T8 were not shown because the interaction "year × treatment" was quite constant over time; therefore, what was said about the main effect (treatment) still holds here. Figs. A.3 and A.4 show the temporal trend of T1, T2, T3 and T6.

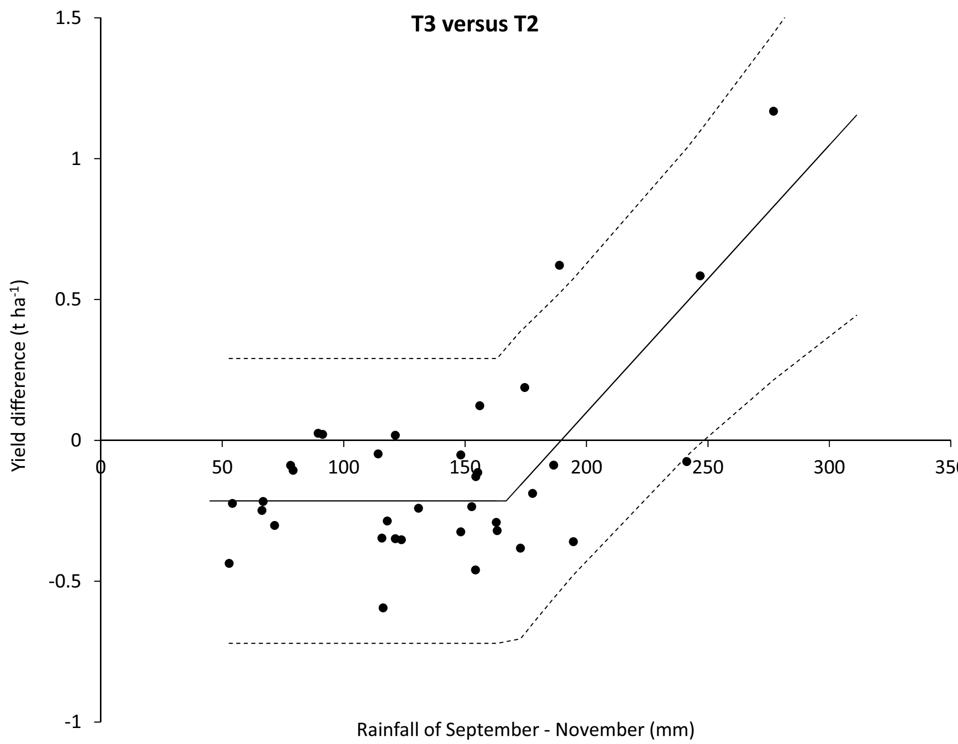

Fig. 3. Relationship between the yield difference of T3 and T2 and the rainfall fallen from September 1st to November 30th (Rain) The symbols represent the observed values. The continuos line is the fitted spline equation: $Y = Y_{T3} - Y_{T2} = -0.21\ \mathrm{t\,ha^{-1}}$ if Rain $\leq$ 167 mm; $Y = -1.79 + 0.00949 \times$ Rain if Rain $\geq$ 167 mm. $R^2 = 0.487$ ($P < 0.0001$). The dashed lines rapresent the lower and upper bounds of approximate 95% confidence interval.

For both GPC and HTW, there was a smaller differentiation among the three year groups compared with what was detected for grain yield.

Considering the entire period of 36 years, no statistical differences in GPC were found in 12 years (33%). In the remaining years, T1 always showed the lowest annual value whereas T2 was not statistically different from T3 and T6 in 15 years. In comparison to T1 and T2, T3 and T6 had greater GPC values in 24 years.

As regards HTW, in 18 years there were no statistical differences among the selected four treatments. In the remaining years, T2, T1, T6 and T3 recorded the highest values in 15, 13, 12 and 4 years, respectively.

4. Discussion

4.1. Dynamics of yield, GPC and HTW

The dynamics of yield, GPC and HTW of winter durum wheat did not show any decline as usually expected when a monoculture is carried out for a long time. An important source of temporal variability in our study might have been the sequence of the 6 cultivars that were adopted in cycles of 5 years. As a consequence, we detected a positive linear trend explaining about 25% of the overall variability of the average annual yield and GPC (Fig. 2). However, temporal variability of productivity was mainly affected by meteorological factors, such as air temperature and rainfall. Lithourgidis et al. (2006) found similar results in a LTE carried out in Greece for 25 years and ascribed the high temporal variability of wheat yields to the total rainfall during the growing season. However, several other studies reported yield reduction after continuous wheat cropping, compared with most of the considered crop rotations (e.g., Huang et al., 2003; Bahrani et al., 2002). After 20 years of continuous cropping, Paré et al. (2015) found a yield reduction of 600 kg ha^{-1} in barley monoculture in the last five years, whereas field pea monoculture decreased yields by about 1000 kg ha^{-1} in most years compared with other crop rotations included in the field experiment.

In a similar LTE started in 1990 at the same experimental farm, Castellini et al. (2014) evaluated the temporal changes of nine indicators of soil physical quality after 20 years of continuous management. The results revealed substantial equivalence between burning and incorporation of stubble and straw and generally good soil physical quality for both treatments.

For the same soil under investigation, recently Castellini et al. (2015) have also demonstrated as the biochar addition to a clay soil may represent a strategy to increase the water retention close to saturation. This represents an advantage in periods of low precipitation since may mitigate water stress.

Results of other long-term studies with various crops showed a reduction of soil organic matter. However, the rate and magnitude of such reduction is related to climate conditions and soil characteristics and it can be counterbalanced by appropriate agronomical practices, such as manure additions, adequate fertilization and return of CRs to soil (Reeves, 1997). Our results, in agreement with Lithourgidis et al. (2006), support the conclusion that, with adequate annual fertilization and effective weed control, continuous wheat cropping may be used for many years without significant yield decline especially for soils, such as clay soil of our LTE, characterized by a good initial availability of total organic carbon and nitrogen.

4.2. Crop residue management

Higher wheat grain yields and hectolitric weight were reported under straw burning compared with incorporation for the treatments with no nitrogen fertilization and autumn irrigation. In many years of this experiment, the yield differences between CR burning and incorporation were not statistically significant. Moreover, in the remaining years the differences were lower than 10% resulting often actually insignificant, especially if they are compared to those due to meteorological pattern over the 36 study years.

In comparison with burning, wheat grain yields were significantly lower of 130 and 250 kg ha^{-1} when straw was incorporated without and with 50 kg N ha^{-1} as urea, respectively.

Furthermore, straw incorporation caused no statistically significant differences in yield and hectolitric weight compared to the ones related to CR burning when nitrogen and water were added before sowing.

The treatment with 50 kg ha^{-1} of N produced higher yield and HTW compared to the treatments with higher N doses. However, this minimum addition of N was effective only when good soil moisture conditions occurred as with 50 mm irrigation for the treatment T6 or under treatment T3 in those years characterised by enough rainfall fallen from September to November.

Therefore, the incorporation of straw residues quite likely increased the need of N fertilizer to produce comparable grain yields to those obtained with burning, although sufficient soil water availability is necessary to fully benefit from this practice. The result can be ascribed to N immobilization from residue incorporation and is in accordance with those obtained by Limon-Ortega et al. (2008). These researchers, examining the effects of straw burning and CR incorporation on grain yield and N use efficiency of wheat, observed that incorporation of organic material with high C:N ratio, such as residue of wheat and maize, led to N immobilization. As a consequence, wheat grain yields were significantly lower when straw was incorporated than when it was burned, obtaining a yield reduction of 200 kg ha^{-1}, very close to the mean yield difference between CR burning and incorporation treatments in our study. A deeper understanding of the causes that led to these results was obtained by Montoya-González et al. (2009) in a field experiment carried out in Ciudad Obregón (Mexico), in a dry environment characterised by mean annual rainfall of 381 mm, with 253 mm from June to August. The Authors, investigating how these alternative practices applied for 9 years affected CO_2 emission and N mineralization, found that CR burning increased N mineralization and decreased microbial activity and consequently CO_2 emission. However, higher N mineralization rates after CR burning explained the increase in wheat grain yields. Differently from our results, the authors observed higher wheat grain yields under urea fertilization. This disagreement is more likely due to the different rainfall pattern in the two arid environments. In Ciudad Obregón, more than 65% of rain (253 mm) falls between June and August, whereas in Foggia the rainfall from September to November is not always enough to ensure the optimum water content for CR decomposition and urea hydrolysis.

On the other hand, Kumar and Goh (2002) found significant interaction between the kind of CR and management treatments with lower soil N mineralization occurring when non-leguminous residues were incorporated as compared with mulching and burning.

In literature, other agronomical practices, such as urea fertilization and irrigation, were evaluated for their capability to mitigate the adverse effects of wheat residue incorporation on N immobilization. Yadvinder-Singh et al. (2004) underlined that the incorporation of green manure with narrow C/N ratio was able to counterbalance N immobilization.

CR burning caused a reduction in GPC compared to CR incorporation with urea fertilization, providing a mean value of 14% which is slightly lower than the optimum threshold required for durum wheat (14.5%). This threshold value was generally exceeded when CR incorporation followed urea fertilization with the lowest amount of 50 kg ha^{-1}, resulting in a GPC of 15 and 15.3% under T6 and T3, respectively. The lower GPC for burning can be due to no N fertilization before sowing.

Considering the threshold values of HTW, which characterize the quality classes of durum wheat grain, all the eight treatments fell in the second highest class with mean HTW ranging between 75 and 78 kg hl^{-1}.

Many researchers examined the effect of CR management practices on yield showing that the results from these experiments are often conflicting because of a number of factors involved. Therefore, no residue management system is universally superior under all experimental conditions.

As reported by Kumar and Goh (2000) in an extensive review, under conditions of optimum fertility, adequate soil water supply and absence of pests and diseases, the yields can be largely unaffected by CR management. However, CR management shows different performance in grain yield when pest and disease are present (Prew et al., 1995) and under low soil moisture and high temperature conditions during the growing season (Lafond et al., 1996). In other words, CR management is expected to affect yield differently in favourable or unfavourable years. Borrelli et al. (2014), in a LTE of maize in northern Italy, found that the effects of both rotation and input are more pronounced in low-yielding years than in high-yielding years in accordance with Porter et al. (1997), and that the yield benefits of crop rotations over monoculture are greater in low-yielding than in high-yielding environments.

The results of our research were somewhat in disagreement with this tendency. In fact, within the three groups of years of low-, medium- and high-productivity, variability among the treatments did not differ ranging between 10 and 30% with very few exceptions. However, in the third group of high-productive years, the T3 treatment (CR incorporation with 50 kg N ha^{-1} of urea without irrigation) provided the highest yield.

On the basis of the chemical monitoring of soil carried out after 31 years of continuous management (Ventrella et al., 2011) incorporation of stubble and straw appeared to be in line with the objective of conserving soil fertility by maintaining the existing level of soil organic carbon. On the contrary, CR burning determined a reduction of the humic and fulvic acids fractions in the soil.

In comparison to crop residue incorporation without nitrogen fertilization and water supply, the productive advantages of crop residue burning, observed in this study and that should tend to disappear in the long term period, do not counterbalance the risks associated with this practice related to biodiversity, road safety and air pollution (Ventrella et al., 2015).

5. Conclusion

A long term experiment was established to investigate the effects of different types of crop residue management on yield response in a continuous cropping system of winter durum wheat. Burning of straw and stubble was compared with their incorporation, considering the agronomical options of nitrogen fertilization and irrigation.

Burning produced greater grain yield and hectolitric weight compared with incorporation. This result may be due to a quite likely higher N mineralization rate after crop residue burning. Conversely, crop residue incorporation seemed to increase the need of N fertilizer to produce grain yields comparable to those obtained with burning, owing to the temporary N immobilization.

However, in some years of the experimental period, differences between burning and incorporation were not significant. In the remaining years they were lower than 10% resulting often insignificant, especially if they are compared to those related to meteorological pattern. Although crop residue burning did not require N supply before sowing, the lack of urea fertilization resulted in a low grain protein content.

The supply of 50 kg ha^{-1} of N as urea, applied just before straw incorporation, can be considered a valid option to mitigate the adverse effects on N immobilization. However, such fertilization is efficient only when good soil water conditions occur during the autumn-winter period, so ensuring microbial activity for crop residue decomposition. In our experiment such good soil water conditions were obtained with irrigation of 50 mm before crop residue incorporation or when rainfall higher than 160 mm from September to November occurred.

Finally, considering that in a long term period burning can result in significant reduction of soil organic matter, crop residue incorporation can thus be considered an effective practice for contributing to maintain the existing level of soil organic carbon, while higher levels of crop productivity could be achieved by ensuring optimal soil N and water availability for residue decomposition.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.eja.2016.02.010.

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