Influence of Previous Crop on Durum Wheat Yield and Yield Stability in a Long-term Experiment

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Abstract

Long-term experiments are leading indicators of sustainability and serve as an early warning system to detect problems that may compromise future productivity. So the stability of yield is an important parameter to be considered when judging the value of a cropping system relative to others. In a long-term rotation experiment set up in 1972 the influence of different crop sequences on the yields and on yield stability of durum wheat (*Triticum durum* Desf.) was studied. The complete field experiment is a split-split plot in a randomized complete block design with two replications; the whole experiment considers three crop sequences: 1) three-year crop rotation: sugar-beet, wheat + catch crop, wheat; 2) one-year crop rotation: wheat + catch crop; 3) wheat continuous crop; the split treatments are two different crop residue managements; the split-split plot treatments are 18 different fertilization formulas. Each phase of every crop rotation occurred every year. In this paper only one crop residue management and only one fertilization treatment have been analized. Wheat crops in different rotations are coded as follows: F_1: wheat after sugar-beet in three-year crop rotation; F_2: wheat after wheat in three-year crop rotation; F_{c+i}: wheat in wheat + catch crop rotation; F_c: continuous wheat. The following two variables were analysed: grain yield and hectolitre weight. Repeated measures analyses of variance and stability analyses have been perfomed for the two variables. The stability analysis was conducted using: three variance methods, namely the coefficient of variability of Francis and Kannenberg, the ecovalence index of Wricke and the stability variance index of Shukla; the regression method of Eberhart and Russell; a method, proposed by Piepho, that computes the probability of one system outperforming another system. It has turned out that each of the stability methods used has enriched of information the simple variance analysis. The Piepho's probability method, moreover, abridges in effective way the analysis of variance results, supplying precise indications about the influence of crop sequence on quali-quantitative productive variables; in particular, wheats in three-year crop rotation (F_1 and F_2) have higher probability to obtain higher qualitative and quantitative productions than one in one-year crop rotations (F_{c+i} and F_c), so as wheat in one-year crop rotation with catch crop vs. wheat monoculture.

Key-words: crop rotation, Southern Italy, stability analysis, wheat.

1. Introduction

Long-term experiments arouse increasing interest worldwide since they represent the source of suitable indicators of sustainable agriculture (not decreasing yield trends, parameters characteristic of the ecosystem quality), useful as early warning systems (Barnett et al., 1995). Moreover, in crop production research, crop rotations represent an agronomic technique aiming to better preserve and more efficiently utilise the available natural resources; in most cases, in fact, a crop in rotation gives higher yields as compared to the same crop in monoculture under identical environmental conditions; this behaviour is explained by the crop rotation effect, whose processes and mechanisms are still not completely known (Karlen et al., 1994), and, currently, no production factor can fully compensate for its effects (Berzsenyi et al., 2000).

Moreover, the analysis of long-term crop rotation data is generally more complicated than that of short-term experiments. The evaluation of several decades of data series requires a specific methodology of data processing and of biometric analysis (annual and combined analysis

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of variance, trend calculations, simulation models). A detailed discussion of the possible problems encountered during the biometrical analysis of crop rotation experiments is reported by Yates (1954); further details are given by Patterson (1953), Castrignanò (1990) and Cady (1991).

Besides, in the analysis of variance of long-term experiment data, the possible statistically significant *treatment x environment* interactions are difficult to interpret due to the complexity of the factors influencing the environment; but they can be easier explained using the yield stability analysis. In the past, the analysis of yield stability has been largely confined to multienvironmental trials of crop cultivar, but the idea of applying these methods to cropping systems is not new (Willey, 1979; Mead and Riley, 1981; Hildebrand, 1984; Raun et al., 1993; Guertal et al., 1994) and Piepho (1998) emphasizes that methods for comparing the stability of cultivars can also be used for comparing different agronomic treatments in general, of which cultivars are only a special case. Since, as previously reported, most of the methods to measure the yield stability has been created for crop cultivar comparison, in the next discussion it will be referred often to genotypes, but the same concepts are valid for cropping systems.

Most stability measures relate to either of two contrasting concepts of stability: "static" (type 1) and "dynamic" (type 2) (Becker and Léon, 1988; Lin et al., 1986). Static stability is analogous to the biological concept of homeostasis: a stable genotype tends to maintain a constant yield across environments or years (Falconer, 1990; Dyke et al., 1995). Dynamic stability, instead, implies for a stable genotype a yield response in each environment that is always parallel to the mean response of the tested genotypes; therefore, the measure of dynamic stability depends on the specific set of tested genotypes, unlike the measure of static stability (Lin et al., 1986).

Stability measures through univariate methods are classified in two broad categories that use either variance or regression methods.

The most common variance methods to evaluate the yield stability according to the "static" concept are: the environmental variance and the coefficient of variability of Francis and Kannenberg (1978).

The environmental variance (S^2), i.e. the variance of genotype yields recorded across years or environments, for the genotype i is computed as:

$$S_i^2 = \sum_{j=1}^{q} \left(X_{ij} - m_i\right)^2 \Big/ (q-1),$$

where,

X_{ij}: yield response of the genotype i in the jth year or environment;

m_i: genotype mean yield across years or environments;

q: number of years or environments.

Greatest stability is $S^2 = 0$.

The equation to calculate the coefficient of variability of Francis and Kannenberg (CV), for the genotype i, is the following:

$$CV_i = \sqrt{S_i^2} \Big/ m_i \cdot 100$$

This last stability index is preferred to the environmental variance (S^2) because often the variance is related to the mean. In this case also, the lower the value of CV, the higher the stability.

The most used variance methods to measure the yield stability according to a "dynamic" yield stability concept are: Wricke's ecovalence (1962) and Shukla's stability variance (1972).

Wricke's ecovalence (W^2), for a genotype i, derives from the following equation:

$$W_i^2 = \sum_{j=1}^{q} \left(X_{ij} - m_i - m_j + m\right)^2$$

where,

X_{ij}: yield response of the genotype i in the jth year or environment;

m_i: mean yield of the ith genotype across years or environments;

m_j: mean yield of the jth year or environment across all tested genotypes;

m: grand mean.

Greatest stability is $W^2 = 0$.

The equation to calculate Shukla's stability variance (σ^2), for the genotype i, is:

$$\sigma_i^2 = \left[\frac{p}{(p-2)(q-1)}\right] \sum_{j=1}^{q} (X_{ij} - m_i - m_j + m)^2$$

$$- \left[\frac{SS(SxA)}{(p-1)(p-2)(q-1)}\right]$$

where,

p: number of compared genotypes;

q: number of years or environments;

X_{ij}:   yield response of the ith genotype in the jth year or environment;

m_i: yield averaged across years or environments of the ith genotype;

m_j: yield averaged across all tested genotypes of the jth year or environment;

m: grand mean;

$SS(SxA)$: sum of squares of the interaction "Genotype x Years (or Environments)".

Shukla's stability variance and Wricke's ecovalence give the same results for ranking genotypes (Becker and Léon, 1988) and the maximum stability is $\sigma^2 = 0$.

The stability analysis by means of regression methods consists in regressing the performance of a genotype onto an environmental index computed as the mean of all genotypes in an environment. The index may be taken as a measure of the productivity of an environment or a year. Regression techniques used to develop stability parameters are based on the slope of the regression line and on the deviations from that slope. A regression with a relatively large slope indicates a genotype with an above-average response to favourable environmental conditions (indicated by the environmental index). The regression approach was first suggested by Yates and Cochran (1938), followed later by Finlay and Wilkinson (1963) and by Eberhart and Russell (1966).

The reference model can be written as:

$$Y_{ij} = \mu_i + \beta_i I_j + \delta_{ij}$$

where,

Y_{ij}: yield response of the ith genotype in the jth year or environment ($i = 1, 2, \dots, v; j = 1, 2, \dots, n$);

μ_i: mean yield of the ith genotype across years or environments;

β_i: regression coefficient, measuring the response of the ith genotype in function of the years or environments;

δ_{ij}: the deviation from the regression line of the ith genotype in the jth year or environment;

I_j: the environmental index obtained as the mean of all genotypes in the jth year or environment minus the grand mean:

$$I_j = (\sum_i Y_{ij} / v) - (\sum_i \sum_j Y_{ij} / vn), \ \sum_j I_j = 0.$$

A stability parameter is, therefore, a regression coefficient estimated in the following way (Finlay and Wilkinson, 1963): $b_i = \sum_j Y_{ij} I_j / \sum_j I_j^2$.

This parameter can be used for evaluating both a type 1 (static) or a type 2 (dynamic) stability: a system tends to the highest "static" stability when b tends to 0, whereas it tends to the highest "dynamic" stability when b tends to 1; in this last case, the instability can be evaluated as the distance in absolute value from the unitary coefficient, i.e. $|b - 1|$. Finlay and Wilkinson (1963) suggested that slopes with $b > 1$ indicate better adaptation to poor environments (they tend to attenuate the year negative or positive trend), while genotypes with $b > 1$ are best used in superior environments (they tend to accentuate the year negative or positive trend). A genotype with a b coefficient proximal to unity shows an average response to environmental conditions, following the positive or negative yearly trend.

Eberhart and Russell (1966) added to the angular coefficient of the regression line another stability parameter; in fact, the deviations $\hat{\delta}_{ij} = (Y_{ij} - \hat{Y}_{ij})$ may be squared and summed to obtain the estimate of a further stability parameter (s_d^2), computed as:

$$s_{d_i}^2 = [\sum_j \hat{\delta}_{ij}^2 / (n-2)] - s_e^2 / r$$

where s_e^2/r is the estimate of the pooled error (or the variance of the mean of a genotype in the jth environment), and

$$\sum_j \hat{\delta}_{ij}^2 = [\sum_j Y_{ij}^2 - (Y_{i.}^2 / n)] - (\sum_j Y_{ij}^2 I_j^2)^2 / \sum_j I_j^2.$$

Lin et al. (1986) interpret the s_d^2 only as an indicator of the goodness of the fit of the regression model for describing the stability, affirming that a poor adaptation of the regression line (i.e. a large s_d^2 value) only highlights the necessity of adopting other type 2 stability indices, whereas a good fit implies little utility of the information given by s_d^2.

Alternatively to the described methods, stability may be assessed in terms of the risk of a system falling below a certain yield level or the risk of one system being outperformed by another (Piepho, 1998). The second type of risk, i.e. the probability that a system 1 outperforms a system 2, in a high number of environments j, is given by:

$$\Pr(D_j > 0) = \Phi\left[\frac{\delta}{\sqrt{\sigma_D^2}}\right]$$

where:

Φ is the standardised cumulated probability function;

$\delta = \mu_1 - \mu_2$;

σ_D^2(variance of the difference D_j in the environment j) = $\sigma_{11} + \sigma_{22} - 2\sigma_{12}$.

As a consequence, the present work aims to evaluate the influence of different crop sequences on yield and yield stability of durum wheat (*Triticum durum* Desf.) in a long term experiment.

2. Materials and methods

The field experiment, still underway at the Centro Didattico Sperimentale "E. Pantanelli" of Bari University, in Policoro area (MT), began in the autumn of 1972, on a deep silty-clay soil. Three crop sequences (a three-year crop rotation: sugarbeet, wheat + catch crop, wheat; a one-year crop rotation: wheat + catch crop; wheat monoculture) in contemporary phases, two crop residue managements and 18 fertilisation formulas are compared (Caliandro et al., 1984). In the experimental design, a split-split plot, the crop rotation is the whole-plot factor, the crop residue management the sub-plot and the fertilisation formula the sub-sub-plot. In this work, only the data collected until 2003 and those relative to one crop residue management and one fertilisation formula (the most common in the cropping area) have been analysed. Wheat crops in different rotations are coded as follows: F_1: wheat after sugar-beet in the three-year crop rotation; F_2: wheat after wheat in the three-year crop rotation; F_{c+i}: wheat in the wheat + catch crop rotation; F_c: wheat monoculture. The following two variables were analysed: grain yield and hectolitre weight. The analysis of variance was carried out for each experimental year and the homogeneity of error variances over the different years was tested through Bartlett test (Gomez and Gomez, 1984). The combined analyses of variance over years were carried out according to the experiment scheme with repeated measures over time (Littell, 1989; Castrignanò, 1990). To this purpose the statement REPEATED of GLM pro-

cedure of SAS/STAT (1987), that implements the "sphericity test" in order to evaluate if, for the "within" effects (YEAR and its interactions), the probabilities given by the common F tests are correct, was used (Huynh and Feldt, 1970). For the rotations, the following three orthogonal contrasts were considered: F_1&F_2 vs. F_{c+i}&F_c; F_{c+i} vs. F_c; F_1 vs. F_2. The yield stability analysis was carried out using: three variance methods, the Francis and Kannenberg's coefficient of variability, the Wricke's ecovalence and the Shukla's stability variance; the regression method of Eberhart and Russell; the method proposed by Piepho that evaluates the probability of a system being outperformed by another one.

3. Results and discussion

Since for some years there were missing data and the error variances over years, evaluated through Bartlett test, were not homogeneous, the number of years considered for the analysis was 26 for grain yield and 22 for hectolitre weight. From the analysis of variance derived that the yields of the three-year rotation wheats (F_1 and F_2) were significantly higher than those of the other wheat crops (Tab. 1). Moreover, between the annual wheats, the hectolitre weight of F_{c+i} was statistically higher. Since the sphericity hypothesis was not rejected, the common F tests were used, not only to evaluate the CROP SEQUENCES "between" effect, but also to verify the significance of the "within" effects (YEAR and its interactions). The variable YEAR and all its interactions resulted highly significant, except, for the hectolitre weight, the interaction "YEAR x F_1 vs. F_2": interactions of difficult interpretation due to the complexity of the factors influencing them.

The results of the stability analysis, obtained with the classic variance and regression methods, were also not always concordant (Tab. 2). From the results of the type 1 stability analyses (Tab. 2), carried out through the Francis and Kannenberg's coefficient of variability (*CV*), wheat monoculture (F_c) showed a temporal instability in relation to grain yield much higher than that of the other wheat crops (*CV* values of 46.0 for F_c vs 23.7-28.8 for the other wheats). As regards the hectolitre weight, the three-year rotation wheats tended to maintain a higher

Table 1. Results of the combined analysis of variance and relative mean values of grain yield and hectolitre weight.

Source of variation		Grain yield			Hectolitre weight		
		d.f.	Variance		d.f.	Variance	
Wheat crops in different rotations	(P)	3	2022.8	*	3	69.8	*
F_1&F_2 vs. F_{c+i}&F_c	(C1)	1	5518.7	**	1	133.7	**
F_{c+i} vs. F_c	(C2)	1	472.0	n.s.	1	49.9	*
F_1 vs. F_2	(C3)	1	77.7	n.s.	1	25.7	n.s.
Error a			85.6			3.5	
Year	(A)	25	632.6	***	21	111.3	***
A*P		75	103.0	***	63	8.9	***
A*C1		25	182.8	***	21	13.5	***
A*C2		25	60.6	***	21	8.7	***
A*C3		25	65.6	***	21	4.6	n.s.
Error b		75	23.4		63	2.8	
		(t ha^{-1})		(kg hl^{-1})			
F_1		4.12		77.8			
F_2		3.95		76.8			
F_{c+i}		3.22		76.2			
F_c		2.79		73.8			

homeostasis level in comparison to the two annual crops; in fact, the homeostasis level (or the level of type 1 stability) is as higher as lower are the *CV* values. From the results of the type 2 stability analyses, carried out with the two variance methods, it came out that the Wricke's ecovalence (W^2) and the Shukla's variance stability (σ^2) values, though varying in absolute sense, gave the same ranking for the compared wheats (Tab. 2), confirming what previously reported (Becker and Léon, 1988). In relation to the grain yield, the F_1 and F_c wheat crops showed the highest W^2 (1333.1 and 1181.6, respectively) and σ^2 values (80.9 and 68.8, respectively) and, therefore, a higher discordance from the average year trend than that shown by F_2 ($W^2 = 629.5$ and $\sigma^2 = 24.6$) and F_{c+i} ($W^2 = 718.6$ and $\sigma^2 = 31.7$). With regard to the hectolitre weight, instead, the wheat monoculture (F_c), showing W^2 and σ^2 values evidently higher than those of the other wheats (W^2 and σ^2 values of 146.3 and 10.9, respectively, vs values of 72-90 and 4-5.5 for the other wheats), showed a higher divergence from the average values across the years in comparison to the other tested wheats.

The stability analyses carried out through the regression method confirmed approximately the results obtained with the variance methods, therefore resulting capable of evaluating both the type 1 and the type 2 stability. Particularly, as regard the "static" stability (type 1), it was possible to observe the perfect correspon-

dence between the b values and those of Francis and Kannenberg's coefficient of variability (*CV*): low b values corresponded to low *CV* values and vice versa. With regard to the measure of the "dynamic" stability (type 2), the values of the parameter s_d^2, rather than those of the angular coefficient b, showed a perfect correspondence with the Shukla variance (σ^2) and the Wricke ecovalence (W^2) values, in relation to the genotype ranking. In relation to the grain yield, the F_1 and F_c wheats, showing b values higher than 1, tended to accentuate the positive or negative year mean trend, to the contrary of

Table 2. Results of the stability analysis through three variance and one regression methods.

Wheat crops in different sequences	CV	W^2	σ^2	b	s_d^2
		Grain yield			
F_1	28.8	1333.1	80.9	1.1	52.3
F_2	23.7	629.5	24.6	0.9	22.2
F_{c+i}	27.5	718.6	31.7	0.8	24.0
F_c	46.0	1181.6	68.8	1.2	41.4
		Hectolitre weight			
F_1	4.3	90.0	5.5	0.7	2.9
F_2	4.8	74.2	4.0	0.9	2.8
F_{c+i}	6.0	72.4	3.9	1.1	2.8
F_c	7.3	146.3	10.9	1.3	5.5

CV: variability coefficient of Francis and Kannenberg; W^2: Wricke's ecovalence; σ^2: Shukla's stability variance; b and s_d^2: angular coefficient and variance of deviations from the regression line of Eberhart and Russell, respectively.

Table 3. Stability analysis through the probability of the i-[th] rotation being superior to the i'-[th].

i-[th] rotation	i'-[th] rotation			
	F_1	F_2	F_{c+i}	F_c
	Grain yield			
F_1	-	0.58	0.78	0.85
F_2	0.42	-	0.81	0.85
F_{c+i}	0.22	0.19	-	0.71
F_c	0.15	0.15	0.29	-
	Hectolitre weight			
F_1	-	0.66	0.67	0.83
F_2	0.34	-	0.59	0.76
F_{c+i}	0.33	0.41	-	0.77
F_c	0.17	0.24	0.23	-

the F_2 and F_{c+i} wheats that showed a higher homeostasis level. In relation to the qualitative yield aspects (hectolitre weight), the wheat after sugarbeet in three-year rotation (F_1) showed the highest homeostasis level.

However, with the variance and regression methods so far described, the yield stability tends to be evaluated only in absolute sense, whilst the evaluation of the risk of having low yields could be more important; in fact, it is usually easier accepted a large yield variability if the yields maintain a high average and not the contrary. The method proposed by Piepho, considering both the mean and the variance, gives unequivocal results (Tab. 3); for instance, the probability for wheat F_1 of having a grain yield higher than wheat after wheat in three-year rotation, wheat + catch crop in interannual rotation and wheat monoculture is of 58, 78 and 85%, respectively. The F_1 wheat, therefore, has a probability higher than 50% to give values of the considered variables (grain yield and hectolitre weight) greater than those reached by the other wheats; the F_2 wheat has a high probability (81-85% for grain yield and 59-76% for hectolitre weight) of giving values greater than the annual wheats and, between them, the superiority of the wheat + catch crop is clear (probability of 71% and of 77% that wheat + catch crop gives grain yield and hectolitre weight values higher than those of wheat monoculture).

4. Conclusions

As stated so far, it is clear that the stability analyses may add crucial information when comparing different agronomic treatments. It came out that each method for stability evaluation has its own characteristics that have to be known in order to correctly interpret the results and use them in relation to the trial aims. Moreover, it has been shown that each of the methods used to evaluate the yield stability has enriched of information the analysis of variance. Furthermore, the method proposed by Piepho seems to summarise effectively the analysis of variance results, giving accurate and unequivocable indications about the influence of a cropping system or crop sequence on the probability of outyielding the other compared systems. In particular, the method has well highlighted that F_1 and F_2 have a higher probability of reaching the highest quantitative and qualitative yields in comparison to the interannual rotation wheat, such as the latter in comparison to the wheat monocolture.

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