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Broccoli yield response to environmental factors in sustainable agriculture

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ABSTRACT

A reduced rank factorial regression was carried out to assess effects of environmental factors in sustainable agriculture on yield performances of homogeneous (one F1 hybrid) and heterogeneous (one landrace, LR, and two derived synthetics) broccoli varieties under Organic Agriculture (OA) and Low-Input (LI) management systems. The study was motivated by a general lack of data on environmental variables that affect broccoli yield. Agronomic trials were carried out for three years in three locations in Central Italy with different pedo-climatic conditions. Reduced rank factorial regression was efficient in summarising the effect of environmental variables on the pattern of Genotype (G) × Environment (E) interactions.

Nitrogen content, together with rainfall, minimum temperature and clay content, were the most important environmental variables and explained 91% of the variability in the G × E interaction matrix. A mild and nitrogen-rich environment allowed good performances to be achieved with all genotypes and maximised the F1 hybrid yield. The synthetic varieties and the LR tolerated a high clay content, even though broccoli crops prefer, in general, alluvial, deep and permeable soils without water stagnation. This suggests that the above mentioned varieties are the best materials for these yield-limiting environments, possibly because they were selected under those conditions.

The results highlight the needs (i) to carry out further agronomy research aimed at identifying the most suitable areas and optimizing the control of environmental variables in OA and LI (in particular, type, quantity and time of application of N fertilization), (ii) to develop specific breeding programs for OA and LI and, while carrying them out, (iii) to evaluate the responses of the genotypes under selection to limiting environmental variables.

1. Introduction

Broccoli, *Brassica oleracea* L. var. *italica* Plenck., syn. [*B. oleracea* L. ssp. *capitata* (L.) DC. *convar. botrytis* (L.) Alef. var. *italica* Plenck; Hammer et al., 2013] is an important crop and its world commercial production, together with that of other *Brassica* vegetables, is estimated over 89 million tons per year (FAOSTAT 2011). The estimated production in Italy is about 426,000 t (ISTAT 2011). Concerning its environmental sensitivity, broccoli shows little tolerance to cold and windy climates, preferring mild and bright environments, with moist and well-drained soils and neutral pH (Branca, 2008).

At present, broccoli world production is mainly oriented towards green big head types, referred to as the “calabrese types”, and is obtained from F1 hybrids that are differentiated for their seasonal growing period. F1 hybrids are very uniform (e.g. genetically and morphologically); they are generally small sized plants, with short vegetative time, which give big sized compact heads as the main harvest (most of them show absence of secondary shoots and heads) (Branca, 2008).

In Italy, in recent decades, F1 hybrid cultivars mostly replaced traditional landraces (LR), although in some regions broccoli LR are still cultivated (Branca, 2008; Ciancaleoni et al., 2013; Negri et al., 2013). LR show great variability and are mainly distinguished from each other by different harvesting times and cold requirements for flower induction, sprouting habit, leaf shape and colour. Head size, grain, colour and angle of curvature are also important distinguishing characters (Branca, 2008). LR are locally appreciated for their taste, which explains their maintenance; the heads (often much

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smaller than those of F1 hybrids) and also the sprouts and the young leaves are used.

Replacement of broccoli LR with F1 hybrids occurred during the 20th century, because the latter were specifically improved for the challenges of modern high input agriculture. However, Torricelli et al. (2014) have questioned whether F1 hybrids are the most suitable materials for Organic Agriculture (OA) and Low-Input agriculture (LI), where stability and reliability under unfavourable conditions might be the key factors. Indeed, these authors have provided evidence of higher stability of a LR and synthetic varieties (see Smith, 2004 for a definition of synthetic varieties) in respect to F1 hybrids in OA and LI conditions and attributed it to the synthetics and LR heterogeneity resulting in greater plasticity and better contrasting ability to abiotic and biotic stresses in the non-homogeneous conditions of OA and LI. A better stability under sub-optimal cropping conditions of LR and heterogeneous varieties (such as open pollinated/synthetic varieties) with respect to F1 hybrids and modern cultivars has been recurrently mentioned in plant breeding literature (van Oosterom et al., 1993; Voltas et al., 1999; Lasa et al., 2001; Yahiaoui et al., 2014). In addition, there is general acceptance that high levels of genetic variation within populations improve the potential to withstand and adapt to novel biotic and abiotic changes including the tolerance to climatic changes (Jump et al., 2009).

However, the debate is still open and, in fact, some authors indicate that traditional cultivars may not necessarily be the best choice in environments managed organically (Poutala et al., 1993; Zand and Beckie, 2002; Kitchen et al., 2003; Kogbe and Adediran, 2004; Carr et al., 2006; Stalenga and Jończyk, 2008; Stagnari et al., 2013).

Finally, it is noteworthy that crop yield is largely determined by climate conditions during growing season and deviations from optimal conditions can seriously affect it.

Therefore, a better knowledge of the effect of environmental factors on crop growth can both improve agronomic technique to contrast adverse environmental conditions and improve the selection of specific cultivars to be grown in target regions (Marjanović-Jeromela et al., 2011) or in environmentally friendly agriculture.

In this respect, and due to the occurrence of climate changes, the study of Genotype × Environment (G × E) interaction has become increasingly important in recent years (Braun et al., 2010). The comparison of F1 hybrids, synthetic varieties and LR in specific environments is a common approach for the evaluation of performances and for the identification of traits related to yield improvement (Ceccarelli, 1996; Annicchiarico, 2002; Voltas et al., 2002). With specific reference to broccoli breeding and cropping, the analysis of the G × E interaction becomes fundamental in the Mediterranean regions (from which most of the commercial production comes), as they are characterised by high inter-annual variability in climate factors, and therefore in yield. Such variability is even enhanced in OA and LI, where conventional agronomic inputs cannot be used to guarantee yield stability.

G × E interaction can be studied by using either linear models, such as joint-regression (Yates and Cochran, 1938; Finlay and Wilkinson, 1963; Eberhart and Russell, 1966; Perkins and Jinks, 1968) and factorial regression (Denis, 1980, 1988), or multiplicative models such as Additive Main Effects and Multiplicative Interaction (AMMI) (Gollob, 1968; Mandel, 1971; Gauch, 1992), Genotype main effect and Genotype × Environment interaction (GGE) (Yan et al., 2000) and reduced rank factorial regression (van Eeuwijk, 1995). Amongst multiplicative models, reduced rank factorial regression, routinely used in vegetation science and generally named as redundancy analysis (Legendre and Legendre, 1998), tries to model the 2-way matrix of G × E interaction effects as function of some measured environmental variables. If the resulting model shows good fit to the observed data, the fitted G × E matrix can be used as the starting point for Singular Value Decomposition (SVD), instead of the observed G × E matrix (van Eeuwijk, 1992). In this way, the results of reduced rank factorial regression can be displayed on a biplot, which contains (i) genotypic scores and (ii) environmental scores. Apart from these, a biplot from reduced rank factorial regression contains also (iii) the coefficients for the environmental variables, projecting them within the canonical axes and helping assess their effect on G × E interaction (van Eeuwijk et al., 1995).

Considering the scarcity of literature data about G × E interaction and about the effects of environmental factors in such an important crop as broccoli (only one reference available, i.e. Torricelli et al., 2014), a study on G × E interactions in homogeneous and heterogeneous varieties becomes relevant to support breeding programs and cropping in OA and LI.

This paper represents a follow-up of the above mentioned Torricelli et al. (2014) study, which gave an account of the better stability of a LR and two synthetic varieties than a F1 hybrid in OA and LI. Here, extending data recording over one year, analysing a different set of results and using different statistical approaches, we aimed at (i) determining the main sources of variation for broccoli yield in OA and LI; (ii) analysing the G × E source of variation by (iii) characterising and identifying the factors that affect yield of different types of varieties and (iv) comparing the yield performances of homogeneous and heterogeneous varieties in OA and LI.

2. Materials and methods

2.1. Plant materials and experimental design

Two synthetic varieties (Syn1_4C and Syn1_8C) developed specifically for OA and LI, the Umbrian LR from which synthetics were developed (Ciancaleoni et al., 2014) and the commercial F1 hybrid Santee (Elsomseed company, one of the few broccoli hybrids that can be used in OA) were assessed for yield. Syn1_4C and Syn1_8C were selected from a Syn0_4C and a Syn0_8C (each obtained by intercrossing 4 and 8 components, respectively) that shared 4 components. The components were specifically selected for OA from the original LR (on the basis of vigour, plant height and diameter and number of inflorescences) and seed propagated under isolation.

Field experiments were conducted for three consecutive years (2011–2013) at three locations in Central Italy: one organic (PG_OA) and one low-input (PG_LI) site in Perugia (Umbria), together with one low-input site in Grosseto (Tuscany) (GR_LI). These sites can be regarded as representative of the different climatic conditions of Central Italy. Overall, nine "year-location" combinations were considered in this study and the term "environment" will hereafter be used to define each of these combinations (i.e. PG_OA_2011, PG_OA_2012, etc.).

The same management practices were applied both in OA and LI, with small differences relating to the fertilisers (see below). In all locations and years, *Vicia faba* L. subsp. *minor* Beck followed by *Hordeum vulgare* L. were subsequently grown in the preceding years. Seedbed preparation was based on ploughing and harrowing after the harvest of the preceding crop. Broccoli was sown in polystyrene trays with 60 cells at the beginning of July and field transplanting was carried out at the beginning of September, using the same experimental layout. Each entry (variety) was randomised in a complete block design with four replicates where each replicate included 10 plants per entry. Spacing amongst plants was set at 1 × 1 m because the LR and synthetics are very vigorous and this spacing is generally used by farmers growing the LR. Fertilization in OA was ensured by pre-implant livestock manuring, by using 1 t ha^{-1} of the commercial product NUTEX LETAME (Agroqualità, 3% N and 3% P_2O_5 content), that was incorporated by using a rotary