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Evolutionary breeding for sustainable agriculture: Selection and multi-environmental evaluation of barley populations and lines

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ABSTRACT

Varieties specifically bred for organic and low-input agriculture are presently lacking. A strategy to develop them is evolutionary breeding that relies on a combination of natural and artificial selection. This study investigated the ability of an evolutionary breeding program, carried out over 24 years, to select barley (*Hordeum vulgare* L.) heterogeneous populations and lines characterized by high grain yield and yield stability across different environments under organic and low-input conditions. A Composite Cross population (named AUT DBA) was initially developed by crossing Parental Populations highly productive under low-input conditions in Central Italy and diverse for several morpho-phenological traits. The AUT DBA was then multiplied for nine years under a low-input management system without any artificial selection.

Three cycles of artificial selection (from 2007/08 to 2009/10) were conducted by selecting within the AUT DBA plants characterized by high grain yield potential and a favourable combination of traits relevant for organic and low-input agriculture.

A new population (a lines mixture named *mix48*) was then developed by mixing the highest yielding and the most diverse lines; 13 lines were also selected. AUT DBA, *mix48* and the 13 lines were evaluated for four successive years in multi-environmental trials carried out under different pedo-climatic conditions and management systems (organic and low-input) and using nine different lines, selected under high input conditions, as controls.

For each of the 24 entries (i.e. the two populations, the 13 selected lines and the nine controls) grain yield was recorded, and yield stability evaluated by using AMMI analysis, Shukla's stability variance and Environmental variance. Average yield and yield stability indexes were calculated over all Environments and for low and high productive Environments, respectively. Finally, the effects on yield of climatic and soil characteristics were evaluated by using a reduced rank factorial regression analysis.

The grain yield of the AUT DBA and *mix48* populations were significantly higher than four of the nine controls. On average, the two populations and the lines selected from them significantly out-yielded the recently developed lines in low-productive trials ($P \leq 0.05$), while no significant differences were detected in the high-productive trials. Across all the tested Environments, the populations showed a higher level of dynamic stability than the controls; six selected lines were also as stable as the populations. The two heterogeneous populations and four of the selected lines, showing the best combination of grain yield and both dynamic and static stability, could be recommended for use in Central Italy under organic and low-input management systems. The main conclusion of this work is that evolutionary breeding is indeed a low-cost and effective approach to develop both populations and lines for sustainable agriculture especially when carried out under low-input conditions.

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1. Introduction

A shift from the conventional agricultural model of growing crops to organic (OA) and low-input (LI) agriculture is recognized as a way to improve sustainability of food systems (De Shutter,

Abbreviations: CCP, composite cross population; PPs, parental populations; LI, low-input; OA, organic agriculture; EBP, evolutionary breeding program.

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2014; Litrico and Violle, 2015; Rigby and Cáceres, 2001; Wezel and Soldat, 2009). OA is a highly heterogeneous production system because of the lack of buffering effect from external input, just like LI and especially in marginal environments (Ceccarelli and Grando, 2005). These systems have suffered from the lack of varieties specifically developed (Lammerts van Bueren et al., 2011, 2002; Murphy et al., 2007; Wolfe et al., 2008) and over 95% of varieties currently used in OA were bred for conventional agriculture (Lammerts van Bueren et al., 2011). In fact, traditional plant breeding programmes have produced many successful genetically uniform cultivars, like lines and hybrids in predominantly self- and cross-pollinated crops, respectively, that are high yielding in high input production systems. These cultivars have been generally bred in tightly controlled growing conditions and under good nutrient availability (Newton et al., 2010 and refs. therein). The utility of breeding programs specifically developed for OA and LI is still debated (Crespo-Herrera and Ortiz, 2015 and refs. therein) because in some cases conventionally bred varieties perform similarly to organically bred varieties under organic condition (Annicchiarico et al., 2010; Hildermann et al., 2009; Saastamoinen et al., 2004). Few examples of breeding programs specific for OA have been carried out in the past (Torricelli et al., 2014 and refs. therein).

A strategy to develop new varieties for OA and LI is the implementation of an Evolutionary plant Breeding Program (EBP) (Suneson, 1969, 1956). EBP relies on the combined effect of natural and artificial selection acting on heterogeneous populations, like Composite Cross Populations (CCPs) or mixtures, composed of competing genotypes (Jain, 1961). The success of an EBP depends upon recombination and segregation and to the extent to which genotypes survival is positively correlated with their agronomic value (Allard and Hansche, 1964). Recently, researches have been carried out to unveil its utility for the development of cultivars for sustainable agriculture in cereals (Döring et al., 2010; Goldringer et al., 2006) as well in other crops (Horneburg and Becker, 2008; Lammerts van Bueren and Myers, 2012 and refs. therein). The output of an EBP can be used as new genetic material for future breeding (if a sufficient level of genetic diversity has been conserved) or as source to select individual lines to be eventually released as varieties (Soliman and Allard, 1991).

To develop a successful EBP for OA and LI the parental lines or mixtures components, to use for the creation of an evolutionary population, should be selected among old breeding lines, old varieties (Stagnari et al., 2013) or landraces. This is because they show ability to compete with weeds, allelopathy effects and efficient use of organic nitrogen sources (Crespo-Herrera and Ortiz, 2015; Dawson and Goldringer, 2012; Konvalina et al., 2007; Lammerts van Bueren et al., 2011, 2002; Wolfe et al., 2008) all traits quite different from those required under high input (Donald, 1968) that might have disappeared in modern cultivars (Lammerts van Bueren et al., 2011; Newton et al., 2009). The optimum number of genotypes to be intercrossed or mixed to create an effective evolutionary population is still unclear and needs further investigations. In the pioneering work of Harlan and Martini (1938) an equal number of seeds of 11 barley varieties were mixed, while more complex schemes, involving the execution of several crosses, were followed in this and in other studies (Enjalbert et al., 1999; Suneson, 1956).

The environment and management system where heterogeneous populations are left evolving is another key point for an EBP targeted to OA and LI. Studying different barley CCPs, Patel et al. (1987) suggested that the maximum response to selection is expected when the materials evolve under directional selection pressure of a single, unchanging environment. Indeed, testing the effect of changing location during the natural evolution of barley bulk populations on several quantitative traits, Choo et al. (1980) found that this approach does not broaden adaptation. Similar results were reported by Lohani (1975). Finally, there is a general agreement that breeding for OA and LI should be conducted in the target management conditions (Ceccarelli, 1996a; Crespo-Herrera and Ortiz, 2015; Lammerts van Bueren et al., 2011; Murphy et al., 2007).

In varieties specifically developed for sustainable agriculture, yield stability is considered extremely important since stable genotypes tend to perform better under unfavourable conditions (Annicchiarico, 2002; Lammerts van Bueren et al., 2011; Stagnari et al., 2013). Regarding stability, the static concept refers to the ability of a genotype to perform consistently across different environmental conditions while the dynamic (or agronomic) concept of stability implies that a stable genotype shows a yield response, in each environment, that is always parallel to the mean response of the tested genotypes (Becker and Leon, 1988). To evaluate the stability of a genotype, different indices have been developed including regression slope (Finlay and Wilkinson, 1963), deviation from regression (Eberhart and Russell, 1966), environmental variance and stability variance (Shukla, 1972) and the additive main effects and multiplicative interaction (AMMI) model (Gauch, 1988; Zobel et al., 1988).

Genotype by Environment interaction (GxE) is considered a common limiting factor when stable genotypes are required (Annicchiarico, 2002; Ceccarelli, 2015, 1996b). In particular, under OA and LI conditions, the variability of the environment often has a more pronounced influence on crop yield than in conventional conditions (Wolfe et al., 2008; Newton et al., 2010).

Crop varieties composed of different genotypes are expected to be more stable than uniform varieties especially in OA and LI. In these systems, where inputs are not sufficient to offset environmental stresses generating a risk of poor crop performance, genetic variation may act as primary mechanism for buffering environmental fluctuations (Döring et al., 2015; Murphy et al., 2005). Heterogeneous populations, especially those developed through EBPs where natural selection can improve traits whose importance may not be recognized in a conventional breeding program, could be the ideal materials to increase yield stability. The role of intra-specific diversity in stabilizing crop production has been suggested by Newton et al. (2010 and refs. therein) and Soliman and Allard (1991). However, not many experimental data are available on this topic and especially for sustainable agriculture.

In this paper, we present the results of an EBP for OA and LI carried out over 24 years by the Dipartimento di Scienze Agrarie, Alimentari e Ambientali (DSA3) to develop high yielding and stable materials (either populations or lines) in OA and LI conditions in different locations in Central Italy. In particular, the aims of the research were to test: (i) the usefulness of the implemented EBP; (ii) yield and yield stability of selected materials under different agro-climatic and management conditions, and (iii) the effect of intra-specific diversity and of different pedo-climatic factors on grain yield and yield stability.

2. Materials and methods

2.1. AUT DBA population development

The CCP named AUT DBA (AUT stands for "autumnal sowing" and DBA is the former Department acronym) was initially obtained by crossing seven different Parental Populations (PPs) to obtain an evolutionary population characterized by high yield under low-input conditions and by sufficient genetic diversity to evolve. This was achieved by selecting PPs that were good performers under LI conditions in Central Italy out of a large number of breeding lines, cultivars and landraces provided by the International Center for Agricultural Research in the Dry Areas (ICARDA, Beirut, Lebanon) (Negri and Petti, 1995). The PPs represented a very large array

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