

# Organic agriculture and evolutionary populations to merge mitigation and adaptation strategies to fight climate change

## Agricultura orgánica y evolución de poblaciones para fusionar estrategias de mitigación y adaptación para combatir el cambio climático

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### ABSTRACT

Organic agriculture mitigates the effects of climate change, is more sustainable than industrial agriculture, provides more nutritious and healthy food, and several ecosystem services. However, its potential to feed the world is largely unexplored, due to the limited number of breeding programs addressing the need of varieties specifically adapted to organic systems. Consequently, organic farmers often cannot find organically produced seed of suitable varieties. This paper presents a plant breeding scheme which combines the use of evolutionary population with decentralized and participatory selection, to serve a multitude of diverse target populations, from environments including those of organic agriculture.

**Keywords:** *Specific adaptation, selection, biodiversity, heterogeneous populations, participation*

### RESUMEN

La agricultura orgánica mitiga el efecto del cambio climático, es más sostenible que la agricultura industrial, y proporciona alimentos más nutritivos y saludables y una serie de servicios ecosistémicos. Sin embargo, su potencial para alimentar al mundo está en gran parte inexplorado debido al número limitado de programas de mejoramiento que abordan la necesidad de variedades específicamente adaptadas a los sistemas orgánicos. En consecuencia, los agricultores orgánicos a menudo no pueden encontrar semillas de variedades adecuadas producidas orgánicamente. El artículo presenta un esquema de fitomejoramiento, que combina el uso de población evolutiva con la selección descentralizada y participativa, a fin de servir a una multitud de poblaciones objetivo diversas de ambientes como los de la agricultura orgánica.

**Palabras clave:** *adaptación específica, selección, biodiversidad, población heterogénea, participación*



## Introduction

In recent years, there has been rapid growth in organic agriculture, which in 2018 was practiced in 186 countries on 71.5 million ha, up from 11 million ha in 1999, by 2.8 million farmers, with global sales totaling more than 95 billion euros (Willer et al., 2020).

Organic agriculture is based on agroecological principles (Bàrberi and Bocchi, 2019), which include biodiversity, in the sense of adapting crops to the physical and social environment. This is radically different from industrial agriculture, which modifies the physical environment with agrochemicals making similar even environments far from each other, and ignoring the social environment (Desclaux et al., 2011). The consequence is the typical monoculture and uniform landscape which characterizes industrial agriculture (Kremen and Miles, 2012).

However, most of the comparisons between organic and industrial agriculture focus on the use of agrochemicals (Ponisio et al., 2014) and therefore on the benefits for human health (Baudry et al., 2018), the benefits for the planet because of the mitigation effects, and on the yield gap between organic and industrial agriculture (Reganold and Wachter, 2016). Comparisons focusing on yield under organic and industrial agricultural systems are skewed by the presence of significant genotype x system interactions (Murphy et al., 2007).

From a plant breeder's perspective, organic agriculture represents a heterogeneous target population of environments (TPE), entirely distinct from the more homogenous TPE typical of industrial agriculture. In the latter, the use of pesticides and chemical fertilizers has a powerful effect in smoothing most of the differences between agronomic environments, even those which are geographically distant, except for those differences associated with temperature.

Thus, both the breeding strategies deployed to deliver varieties to industrial agriculture and the centralized seed systems associated with them, both based on a negative interpretation of genotype x environment interaction (GEI) (Ceccarelli, 1996), cannot possibly serve organic agriculture.

To serve a heterogeneous TPE, characterized by a variety of climates, soils, landscapes, farming practices, customers and markets, a highly flexible and dynamic breeding strategy is required, fundamentally distinct from that of commercial breeding.

The aim of this paper is to describe a plant breeding scheme which implements such a strategy.

## The strategy

The strategy is based upon decentralized selection—namely selection conducted independently within each

target environment— combined with participation; that is, selection conducted in partnership with users.

Any such strategy must fit within the framework of a breeding program, which typically involves three main stages (Schnell, 1982; Ceccarelli and Grando, 2019):

(1) *Generating of genetic variability* (including selection of parents, making crosses, crossing techniques, choice of type and number of crosses, introduction of germplasm from gene banks or other breeding programs, or from farmers).

(2) *Selection* of the best genetic material from within the genetic variability created or acquired during Stage 1 (this can be implemented through a variety of methodologies, including molecular tools).

(3) *Testing of breeding lines* (including comparisons between existing cultivars and the breeding lines emerging from stage 2, and the experimental designs and statistical analysis which are appropriate to conduct such comparisons).

Plant breeding does not operate in a social vacuum, and recently it has been acknowledged that two additional and important stages need to be recognized explicitly as part of a breeding program: *social targeting and demand analysis* (Weltzien and Christinck, 2009), and *dissemination of cultivars* (Bishaw and Van Gastel, 2009).

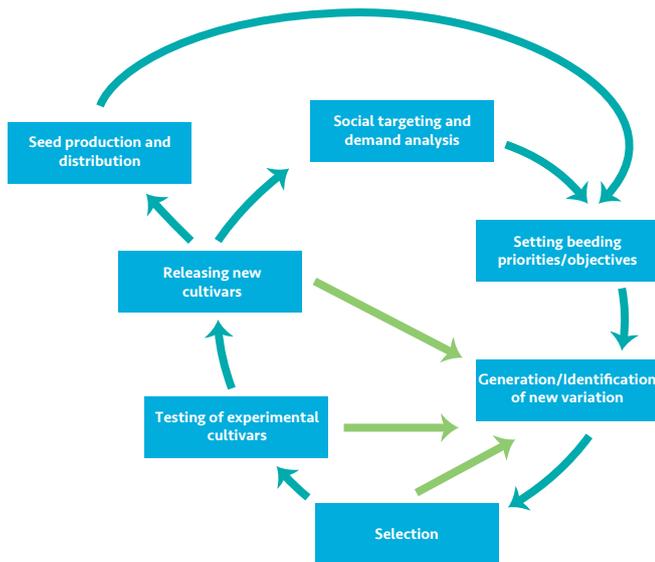
Thus, a breeding program can be schematically represented as in Figure 1.

In social targeting and demand analysis, important tools include **Customer Profile** and **Product Profile** development. These tools address two key questions: **breeding for whom** and **breeding what type of variety**.

A product profile describes a variety (or varieties) with all the necessary characteristics for acceptance by the targeted customer(s) in a particular market, in a given social group, and for a specific type of management. Therefore, the development of a product profile is an important step in the designing of a breeding program, because it keeps a clear description of the characteristics of the variety (or varieties) to be developed. This includes whether the variety should be uniform or heterogeneous, the total area in which is expected to be planted, the type of crop management under which will be planted, the socioeconomic environment, and farmer/consumer expertise.

Within the TPE addressed by a breeding program, and within the boundaries of organic agriculture, it is possible to develop different product profiles for different crops, or different product profiles for the same crop grown within the same location but for different uses—for example in the case of malting, food and feed barley.

Once the product profile has been developed, it is possible to decide **how to proceed**, including the choice



**Figure 1.** Main breeding program stages (modified from: Tufan, H. A., Grando, S. and Meola, C. (Eds.). (2018). «State of the Knowledge for Gender in Breeding: Case Studies for Practitioners. Lima (Peru). CGIAR Gender and Breeding Initiative». *Working Paper*, 3, p. 9. Available online at: [www.rtb.cgiar.org/gender-breeding-initiative](http://www.rtb.cgiar.org/gender-breeding-initiative)).

of germplasm, the breeding method, the number of testing locations, the traits to be measured or scored, the techniques for assessing relevant traits, appropriate experimental designs, suitable data analysis, etc.

The development of a product profile must be conducted together with the development of the customer profile, which includes both a social and a gender dimension. Both tools must be used in a participatory mode with the customer, and therefore participation should begin at the very onset of the breeding program.

Using participatory product development and a customer profile enables the precise physical and social targeting of a breeding program, which can be implemented by decentralized selection.

Decentralized selection constitutes the practical application of a positive interpretation of GEI, based on experimental assessment of the repeatability of genotype  $\times$  location (GL) interaction.

Based on Figure 1 and once a product and a customer profile have been developed, location should be interpreted in a broad sense, given that we are not dealing only with location in the physical sense of the term; in other words, is not only a certain physical place characterized by a given soil and climate, but also social and management aspects such as the type of farming system and the relative importance of the crop, the type of genetic material preferred by farmers, the uses of the crop, the farmers' typology (including wealth, literacy, gender, ethnic group), farm size, the perception of climate change, the level of resilience, etc. (Ceccarelli and Grando, 2007; Ceccarelli et al., 2007; Ceccarelli et al., 2013).

Thus, in a classic two-way GL matrix, different Ls may refer to management and social differences, but they must be situated within the same location. Only then is it possible to conduct an analysis of  $G \times M$  and  $G \times S$  not confused with GL, as would be the case in a  $G \times E \times M$  or  $G \times E \times S$  analysis, regardless of whether E means location or years.

Therefore, in deciding which physical locations to use as a random TPE sample, the breeder should consider not only climate and soil differences, but also, for a given physical environment, management, differences in social and customer preferences, access to credit, farm size, access to market, availability of inputs, labor costs, etc.

Decentralized selection recognizes the fundamental difference between GL and genotype  $\times$  year within location ( $GY_L$ ) interaction (Singh et al., 2006), a difference that is seldom mentioned in even the most recent GEI literature. And yet, more than fifty years ago, Allard and Hansche (1964) specified that  $GY_L$  and GL interactions cannot be combined into GE, because the former is largely unpredictable while GL can be, to some extent, predictable.

These distinctions also make it possible to interpret the underlying causes of GL, whether they are due to interactions between genotypes and locations, specific social factors ( $GL_S$ ) or location-specific management factors ( $GL_M$ ), or a combination of the two.

One implication of decentralized selection is that it makes it possible to select genotypes with a high GL and a low  $GY_L$  interaction; that is, with specific spatial adaptation and broad temporal adaptation. The latter is one attribute of resilience, which can be further enhanced by exploiting the advantages of heterogeneous populations, as illustrated below.

Resilience, defined as the capacity to maintain core functions under disturbance and the ability to adapt to change (Stone and Rahimifard, 2018), must be addressed as part of a breeding program. In fact, one of the effects of climatic change on agriculture is a decline in the resilience of crop systems, as shown recently in the case of wheat in Europe (Kahiluoto et al., 2019), although this remains the subject of debate (Piepho, 2019) and recently a new methodology for the estimating of resilience has been proposed (Zampieri et al., 2020).

Before considering the role of participation in a breeding strategy for organic agriculture, we need to consider another implication of decentralized selection, which was also recognized by Allard and Hansche (1964).

In fact, while decentralized selection can make a positive use of GL interactions by selecting for specific spatial adaptation, varieties well buffered against unpredictable weather fluctuations are the solution to  $GY_L$  further enhancing resilience. This can be achieved through individual and population buffering. While

individual buffering is a property of specific genotypes, and particularly of heterozygotes, population buffering arises through the interactions among the different genotypes within a population, beyond the individual buffering of specific genotypes. Thus, **the advantage of heterogeneous populations is that they can exploit both individual and population buffering** (Allard and Hansche, 1964; Dwivedi et al., 2020).

The recognition that heterogeneous populations, such as evolutionary populations (EP) and mixtures, constitute the ideal genetic materials for a breeding strategy addressing heterogeneous TPE, is particularly important today as a way of coping with the extraordinary complexity of climate change (Ceccarelli and Grando, 2020). Evolutionary populations (also known as Composite Cross Populations or Bulk Populations) are obtained by mixing the seed obtained from the crossing of a number of varieties, while mixtures are obtained by mixing the seed of a number of varieties (Wolfe and Ceccarelli, 2020).

Ceccarelli and Grando (2020) have shown that climate change is a complex breeding objective because:

1. changes in temperature and rainfall are likely to vary from location to location, thus adding to the heterogeneity of the TPE represented by organic farms.
2. climate change is not only about temperature and rainfall, because such changes also affect the distribution and outbreak of pests (Heeb et al., 2019), particularly across the insect spectrum (Zavala et al. 2008; Deutsch et al. 2018) and including pollinators such as bumblebees (Kerr et al., 2015), diseases (Newton et al., 2011; Pautasso et al., 2012) and weeds (Ziska and Dukes, 2010; Colautti and Barrett 2013; Matzrafi et al., 2015);
3. extreme weather events can influence interactions between crops and pests in an *unpredictable* way (Rosenzweig et al., 2001).

This evidence points to climate change as an extremely complex and evolving problem, requiring an evolving solution such as EPs and mixtures (Ceccarelli and Grando, 2020).

A considerable body of research, ranging from the seminal paper by Harlan and Martini (1929) to more recent work (Wolfe et al., 1992; Goldringer et al., 2006; Finckh and Wolfe, 2006; Döring et al., 2011; Raggi et al., 2017; Brumlop et al., 2017; Bocci et al., 2020) shows that EPs and mixtures are able to evolve, adapting their phenology, and increasing their disease resistance, yielding ability and yield stability. There is also considerable anecdotal evidence regarding the ability of EPs to control weeds, a major problem in organic agriculture.

Of particular relevance to organic agriculture is the fact that the type of resistance exhibited by EPs and mixtures is much more durable than the type of resistance obtained by single genes or gene stacking using conventional breeding or genetic engineering, which accelerate the

evolutionary changes in agricultural pests (Palumbi, 2001; Ceccarelli, 2014).

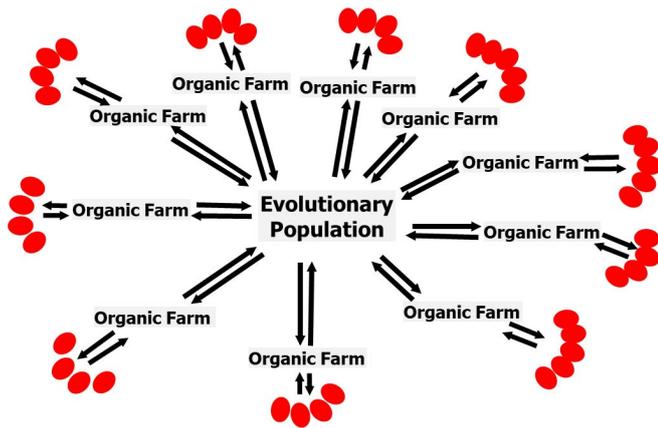
Interestingly, most of the research on EPs and mixtures has been conducted on self-pollinated species such as wheat, barley and rice, suggesting an even greater evolutionary potential on the part of EPs and mixtures of cross-pollinated crops.

Because of this ability, with time the same EP planted in  $n$  sufficiently different locations and propagated with the seed produced in each location, breaks down in  $n$  populations which are each adapted to their own location (including in terms of management). Figure 2 shows the example of divergent evolution of a bread wheat EP made in Syria at the International Center for Agricultural Research in Dry Areas (ICARDA), named the ICARDA evolutionary bread wheat population. Thus, EPs constitute the ideal breeding material for a dynamic response to the challenges of climate change, while adapting to the heterogeneous TPE represented by organic agriculture. In other words, they represent a natural combination of mitigation and adaptation strategies.

The term «dynamic» refers not only to how EPs are developed, but also to the final products of an evolutionary-participatory plant-breeding program. In fact, from the same EP it is possible to obtain a heterogeneous population and/or uniform varieties, at different times or for different markets. The term «dynamic» also refers to the mode of collaboration of scientists-farmers (or, more generally, clients). For example, the degree and the type of scientists' involvement may vary across locations and,



**Figure 2.** An example of divergent selection of an evolutionary bread wheat population: the ICARDA evolutionary bread wheat population after 10 years' evolution in Sicily (left) and the same population after 10 years' evolution in Tuscany (right), grown in Marche in 2020 (courtesy of Pierluigi Valenti).



**Figure 3.** A general model of Decentralized-Participatory Breeding for organic agriculture. The red circles represent the selection sites. The arrows indicate both the flow of material and of information.

over time, within locations: in the former, the mode of collaboration is shaped according to factors such as local habits, traditions, knowledge, socioeconomic conditions and crop use, while the latter reflects an ongoing and reciprocal fine-tuning of roles as the collaboration evolves.

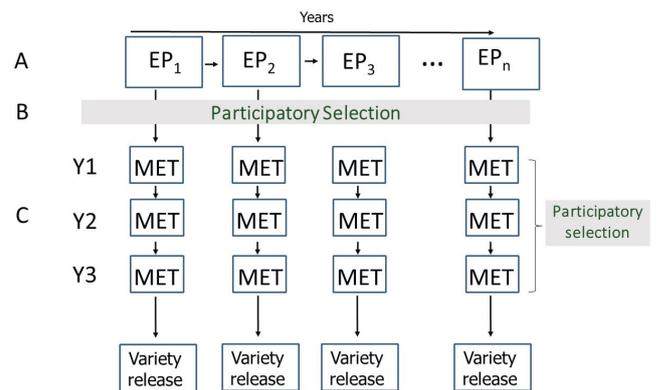
Figure 3 shows a general model of Decentralized-Participatory Breeding for Organic Agriculture (the number of farms is purely indicative).

It should be noted that the EP need not be the same for all the organic farms representing a given TPE. Also, the responsibility for assembling the EP may be assumed by either a formal or an informal institution or association. Rather than a single organic farm, a community of farms may manage the EP, thereby enabling the exploiting of the evolutionary ability of the population to adapt to different environments.

Different philosophies exist for the developing of EPs, either from selected parents or from parents of widely diverse origin, in order to generate as much diversity as possible.

Figure 4 shows the details of the selection process within each organic farm or community of organic farms. While the EP evolves over time (A), farmers, alone or in collaboration with scientists (B), conduct the selection. Selection can be conducted in different ways, depending on the type of variety aimed at by the farm or the community. For example, it is possible to select for uniform material for certain types of market, uses or seed systems, and for heterogeneous material for other types of markets, uses and seed systems. Participation continues (C) during the development of varieties, from the initial selection phase through Multi Environment Trials (MET), conducted in a number of neighboring farms or in different community farms.

The model shown in Figure 4 can be replicated in every TE. The model can easily accommodate the use of



**Figure 4.** The management of an evolutionary population within a single organic farm or within a community of farms.

molecular tools to increase the speed and precision of selection.

In Figure 4, the final stage, variety release, must be reformulated based on the new EU rules for the production and labeling of organic products, which permit the use of heterogeneous material.

## Conclusions

The scheme discussed in this paper has the advantage of being flexible in terms of number of locations and populations, depending on the presence and degree of institutional support. Even in the absence of institutional support, farmers can manage the EP as their crop, conducting selection only in order to generate a sub-population with a certain degree of phenotypic uniformity, for those crops for which this is a market requirement.

Besides the ability to respond to the diversity of organic farms by deploying specifically adapted varieties and/or populations to different farms, this scheme makes farmers independent from large seed companies: where the evolutionary population becomes a commercial crop, it will be in the interest of the farmer to reproduce his/her own seed as the population evolves to become better adapted.

Managing EPs becomes easier when conducted as a community, growing similar crops with a similar vision and objectives. In areas with similar physical and social characteristics, the population is grown by several farmers, to reduce the risk of loss resulting from catastrophic climatic events, while enabling the exchanging of seed to maintain a high level of diversity.

Given the considerable diversity they harbor, EPs may contain the solution to new problems such as, for example, new biotic stresses appearing because of climate change.

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## Authorial contribution

The authors contributed equally to the paper.

## Potential conflicts of interest

The authors declare no conflicts of interest.

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