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Review

Return to Agrobiodiversity: Participatory Plant Breeding

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Abstract: Biodiversity in general, and agrobiodiversity in particular are crucial for adaptation to climate change, for resilience and for human health as related to dietary diversity. Participatory plant breeding (PPB) has been promoted for its advantages to increase selection efficiency, variety adoption and farmers' empowerment, and for being more socially equitable and gender responsive than conventional plant breeding. In this review paper we concentrate on one specific benefit of PPB, namely, increasing agrobiodiversity by describing how the combination of decentralized selection with the collaboration of farmers is able to address the diversity of agronomic environments, which is likely to increase because of the location specificity of climate change. Therefore, while PPB has been particularly suited to organic agriculture, in light of the increasing importance of climate change, it should also be considered as a breeding opportunity for conventional agriculture.

Keywords: biodiversity; participation; decentralization; climate change; human health; climate change; genotype x environment interaction; breeding efficiency

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1. The Importance of Biodiversity

Biodiversity in general, and agrobiodiversity in particular, are important to humans for several reasons: they increase resilience to climate changes by increasing the stability of ecosystem processes [1], benefit health through dietary diversity [2], are important for food security [3] and reduce the risk of yield losses [4]. A literature review [5] reported that diversified farming systems support substantially greater biodiversity, soil quality, carbon sequestration, and water-holding capacity in surface soils, energy-use efficiency, and resistance and resilience to climate change than uniform systems. In other words, biodiversity is beneficial in terms of several ecosystem services. Ecologists have long suspected that the loss of biodiversity could increase the risk of pandemics such as COVID-19 and a recent article [6] provides evidence of the underlying causes of this link.

Despite all this evidence, plant breeding, the science responsible for producing new varieties, has moved, particularly in the last 70 years, towards uniformity [7]. Sir Otto Frankel already, in 1950, warned of the danger in pursuing uniformity: "From the early days of plant breeding, uniformity has been sought after with great determination. For this there are many reasons—technical, commercial, historical, psychological, aesthetic" [8]. He added that the concept of purity "has not only been carried to unnecessary length but that it may be inimical to the attainment of highest production" since it is "concerned with characters which are readily seen but often of little significance". Frankel never used terms such as "scientific" or "biological" reasons.

However, Frankel went largely unheard as today most modern varieties are pure lines, hybrids or clones, depending on the crop and on the market demands. However, the uniformity of varieties alone would not be sufficient to explain the decline in agrobiodiversity because plant breeding could have produced many of them. The decline in agrobiodiversity is due to the predominant philosophy being followed by both public and private breeders with regard to two fundamental concepts, namely, *wide adaptation*, defined as the ability of a variety to perform well across locations, and *stability*, defined as yield consistency across years [9–11]. In fact, despite the evidence from evolutionary biology that locally adapted plants perform better [12] and demonstrate an average 45% higher fitness than introduced genotypes [13], selection for specific adaptation has been rather an exception in plant breeding and only a few studies have measured its impact [14].

Plant breeding has followed the changes in global food systems shifting towards a reduced number of crops [15], with markets' preference for uniformity and standardization [16], thus becoming one of the major drivers of climate change, land-use change and biodiversity loss [17]. In other words, it is the requirements of industrial cultivation, husbandry and processing (and to some extent consumer demand) that determine the breeding objectives rather than nutritional value, taste, improved stress resistance or adaptation to natural conditions [18]. Related to this scenario is the evidence that global agriculture has grown more vulnerable to climate change [19].

With this review, we aim to show the increase in agrobiodiversity that can be achieved by the organization and implementation of a participatory plant breeding program.

2. Decentralized-Participatory Plant Breeding

Plant breeding is a cyclic process during which breeders generate diversity, most commonly by making crosses; select, within the diversity generated during a varying number of years, which depends on the crop, the methodology and the type of variety to be produced; and eventually obtain as a final product a new variety, which in several countries must be distinct, uniform and stable for its seed to be legally commercialized.

The cyclic nature of a plant breeding program implies that each year new crosses are made and therefore, at any moment in time, the breeder handles several generations of breeding material, representing different stages in the breeding cycle. These are usually grown and evaluated in one or more research stations. Their management, including data recording and processing, as well as seed sample storage, are the responsibility of the breeder's team.

The entire process also includes setting objectives and, most importantly, defining a product profile and a client profile or, in other words, defining which type of variety(ies) to breed for, and for which typology of clients. A product profile is the complex of traits that farmers would prefer relative to the varieties they are already growing [20].

Depending on the size of the breeding program, regional, national or international, and on the crop, there could be a number of product profiles and client profiles, and also a number of contrasting physical environments to address, for example, irrigated vs. rainfed, organic vs. industrial, etc.

Faced with this complexity, breeders have historically debated between breeding for wide adaptation and breeding for specific adaptation [21]. Adaptation by natural selection is the fundamental principle of the theory of evolution. An early step in the process of adaptation and diversification is the differential adaptation of populations of the same species [13], hence an increase in within-species diversity. Therefore, in evolutionary terms, adaptation seems to refer to a physical environment represented by a location. However, in breeding terminology, adaptation has been referred to both time and space, since the concept is related to genotype by environment interactions (GEI).

GEI can be defined as the phenomenon by which the same genotype gives different phenotypes depending on E, where E can be a physical location (L), a given year (Y), a combination of locations and years (YL), a type of agronomic management (M) or a social environment (S), and their various combinations, not necessarily factorial.

GEI is one of the most, if not the most often investigated topic in plant breeding for its large effect on genetic gains [22]. GEI considerably complicates the breeder's work, particularly when it is of qualitative type, namely involving a change in ranking. In other words, when tested in diverse locations, some varieties are the top yielding in some locations but bottom yielding in other locations; at the same time, other varieties are the top yielding in different locations. This type of GEI has been named cross-over interaction [23], which makes it difficult for the breeders to decide what to select.

GEI is related to the concept of adaptation because of the fundamental difference between its two main components, namely, genotype x location (GL) and genotype x year (GY). Already 50 years ago, it was clarified that GL and GY cannot be combined because GL can be, to some extent, predicted, as for example when, in a given location, the same variety is performing consistently, year after year, better than others. On the contrary, GY is largely unpredictable, as it depends on year-to-year weather fluctuations [24,25].

While decentralized selection can make positive use of GL interactions by selecting for specific adaptation, varieties well buffered against the unpredictable fluctuations of the environment are the solution to GY. 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 by the interactions among the different genotypes within a population, beyond the individual buffering of the specific genotypes. Therefore, the advantage of heterogeneous populations is that they can exploit both individual and population buffering.

The cyclic aspect of plant breeding is important because the most important agronomic traits are quantitative, and therefore only a modest and incremental improvement in these traits can be made at each cycle [20].

3. Organization of a Participatory Plant Breeding Program

A plant breeding program becomes participatory when clients, generally farmers, but with no limitations to other stakeholders, participate or, as many prefer, collaborate with scientists in all the key steps of the breeding program [26].

Key steps are, for example, setting the objectives of the program, choosing the parents and the type of germplasm (for example, local vs. exotic) and developing the product profile, as well as methodological aspects such as the number of entries, the size of the plots, the agronomic management of the trials and the organization of the farmers' selection process. Farmers can also be involved in making crosses and it has been argued that this is crucial for a program to be truly participatory. However, we believe that, after the choice of the parents and the design of the crosses based on the definition of the objectives, making the crosses is merely a technical operation [26] and therefore, although a useful skill for the farmers to acquire, is not necessarily a measure of the level or quality of the participation.

A participatory plant breeding (PPB) program must maintain the cyclic aspect of plant breeding, because this is a condition for the program to become progressively more accurate in targeting the physical environment, in addressing the clients' needs and in enhancing farmers' skills. The cyclic aspect also allows the necessary flexibility to adapt to changes in objectives, product profiles and client profiles.

As decentralized selection is one of the two pillars on which PPB is based (the other is participation), it is important to test the breeding material in the actual selection environments at the earliest possible stage. A breeding method that we found suitable, particularly in self-pollinated crops, is the bulk method [27–29], which, in its original formulation, consists of advancing separately as bulks, each of the *n* crosses performed at the beginning of each breeding cycle—where *n* can vary from a few hundred in the case of regional programs, to several thousand in the case of international programs—until a satisfactory level of homozygosity is reached within each bulk.

The method is useful in PPB because, depending on the number of locations addressed, segregating populations as early as F_3 bulks can be deployed in each of the selection environments without any previous selection on station. Usually, at the F_3 generation, there is enough seed available for each bulk for the trials to be organized with unreplicated designs, with replicated checks or partially replicated (p-rep) designs [30], which allow comparing the bulks under farmers' agronomic practices in as many locations as the program can manage. The use of suitable experimental designs and statistical analysis allows obtaining an estimate of the best linear unbiased predictors (BLUP) of the genetic merit of the bulks and using them for selecting the best bulks from one stage to the next.

Trials conducted in farmers' fields are expected to be less precise than in a research station; therefore, the choice of suitable experimental designs is crucial. One design, which has proved to be useful in increasing the precision of field trials, particularly in the early stages of a breeding program when there is a large number of genetic materials to be tested and relatively little seed available, is the partially replicated design in rows and columns allowing the control of field variability in two directions [31]. The relative genetic gains for the p-rep designs are significantly higher than those obtained with an unreplicated design with replicated checks, such as the augmented design. The precision can be further increased by generating experimental designs incorporating variable replications and correlated errors with an R-program package called DiGGer [32].

Usually, at least three stages of selection between bulks are conducted. In the second and third stages, trials are replicated among different farmers within the same villages to capture the effect of different agronomic managements. At the end of the three stages, the bulks are at the F_6 generation with a high frequency of homozygotes. At that point, selection begins within the bulks, based on the hypothesis that those bulks, which went through three stages of selection based on their genetic merit and on farmers preferences, must contain a high frequency of superior genotypes. Therefore, they could become sources of pure lines to be further tested to obtain a variety; however, depending on the seed laws of the country, on the crop and on the farmers' preferences, the bulks could also become the new varieties, thus exploiting the benefits of heterogenous material described above.

Other methods are equally suitable and a number of them have been recently reviewed [33], and methods suitable for cross-pollinated and vegetatively propagated crops have been also described in detail elsewhere [28]. Whatever methodology is used, it should allow bringing into farmers' fields as much genetic diversity as possible, from which farmers can choose. The only exception is represented by traits with high heritability, namely with low GEI, which could be conveniently selected within a research station, provided the breeder knows their most desirable expression by farmers. Typical examples of such traits are seed colour, phenology, quality traits and disease resistance.

Another essential feature of a PPB program is that it should maintain the cyclic aspect of a plant breeding program, without which it is no longer a breeding program but simply an experiment on plant breeding.

PPB generates diversity through two mechanisms, which act simultaneously. The first is decentralized selection, which, because of differences in soil characteristics, climatic conditions, agronomic practices, farmers' preferences, gender differences and social conditions among locations, inevitably determines the selection of different genetic material by different farmers in different locations, thus increasing agrobiodiversity in space [34]. The second is the continuous flow of new genetic materials, which favours a rapid turnover of the varieties, thus increasing agrobiodiversity in time. This has been well documented in Syria [35].

On one hand, the agrobiodiversity in time and space generated by PPB is an ecological barrier to the spreading of pests, but on the other, it makes measuring the impact of a PPB program a challenging task. This is because the impact of a plant breeding program is usually measured as the area planted with the varieties generated by the program, or by the number of farmers growing them, or by the percent share of the seed market in the case of private breeding companies. In the case of a PPB program, and as a consequence of the rapid identification and turnover of new varieties, which are selected for specific adaptation, it is unlikely that a single variety expands to a large area before being replaced by another variety.

The cyclic nature of a PPB program caused a remarkable increase over seasons in farmers' skills in a number of countries where PPB was practised; farmers moved from an almost passive participation to various degrees of active participation ranging from suggesting new selection criteria to indicating desirable crosses [36].

One form of participation in plant breeding, which has been described as participatory variety selection (PVS), is when farmers collaborate in the final stages of an otherwise conventional breeding program (namely centralized) to choose among a restricted number, normally around 10–20, of nearly finished breeding lines. Although the method has the disadvantage of considerably limiting the choices of the farmers, it is easier to organize because of the small number of lines and has the merit of being a possible entry point, which could eventually lead to implementing a PPB program. However, the fact that PVS is easier to organize has implied that PVS has been often organized outside breeding programs by organizations not engaged in plant breeding. This usually leads to lack of continuity and, consequently, to a limited benefit to farmers.

4. The Scientific Basis of PPB

A PPB program has the same scientific basis of a conventional breeding program. It differs because the evaluation and the selection of the breeding material are carried out in farmers' fields in collaboration with farmers and other stakeholders to be as inclusive as possible. The locations are chosen to represent the target population of environments and the actual sites where the breeding material is evaluated and selected are chosen, within each location, together with the farmers.

As indicated earlier, the PPB program can achieve a high level of precision by adopting the most advanced experimental designs and statistical analysis. Furthermore, each of the three stages of selection, even if conducted with bulks, is in fact a Multi Environment Trial (MET), namely, field trials conducted in a number of locations and years. Therefore, at an early stage of the PPB program it is possible to obtain information on the bulk responses to the locations and to study the nature of GEI.

The analysis of MET is particularly useful to continuously fine tune the organization of a PPB program. For example, the use of GGE biplot [37] allows the grouping of locations on the basis of the repeatability of GL interactions. In other words, if n locations, among those used routinely in the breeding program, consistently rank the breeding materials in the same way year after year, $n - 1$ of those are redundant and can be discontinued as testing sites, leaving only one. The resources saved can then be used by expanding the program to new location(s). This applies also to MET conducted in conventional breeding programs, but in the case of a PPB program, the ranking of breeding material at different locations, for example for grain yield, must be validated with the ranking of farmers preferences before deciding on redundancy.

Therefore, a PPB properly organized is not only capable of controlling the obscuring effects of uncontrollable within-field, site-to-site, and year-to-year heterogeneity, which has been considered as a limit to PPB's efficiency [38], but also of capturing, to some extent, genotype x management (GM) interactions, as different genetic materials under selections may respond differently to soil fertility, fertilizers, or to other agronomic management techniques. This is achieved by replicating trials at the same selection stage in fields differing in agronomic management within the same village. For example, if, in a village, farmers differ in their fertilizer use depending on their wealth, trials can be planted on the property of different farmers to measure the differences among the breeding material for their response to fertilizer without the confounding effect of climatic conditions.

The efficiency of selection by farmers has been questioned [20], although there is evidence that farmers' selections can be higher yielding on farm than breeders' selections [39,40], or that they have equivalent yield to pure-line varieties, but with traits added, which are important to farmers [33].

One recent criticism addressed the small plot size commonly used in on-farm research as the main reason why participatory research failed to materialize as standard practice, preventing the effective integration of science-based and farmers-based knowledge [41]. In our experience, and with specific reference to PPB, plot size has been one of the organizational issues negotiated with farmers; it varied widely depending on the crop, on the plant breeding stage, on the country, on average farm size and on the need to reach farmers regardless of their farm size [42]. While it was something new for farmers at the beginning of the program, with time they became familiar with (relatively small) plot experiments, which did not preclude them from testing what they considered the most desirable breeding materials on a scale meaningful to them [42].

In fact, the demonstration that it was possible to organize a plant breeding program in partnership with farmers with the same scientific structure used in a research station was the strategy deliberately used to facilitate the institutionalization of PPB.

Eventually, PPB can take full advantage of some of the molecular techniques available to plant breeding such as marker-assisted selection (MAS) and genomic selection, which allow for a greater number of traits to be included in the selection process [43].

One obvious question is: why is PPB not the most common way of carrying out plant breeding, given that is capable of increasing agrobiodiversity with all its associated benefits, and can address the real needs of the stakeholders in a highly inclusive manner?

Before answering this question, it may be useful to see how widely PPB is, and has been, used.

5. Participatory Plant Breeding Globally

Two recent reviews [33,44] have addressed this question. The most recent [33] restricted the search to US, Canada and Europe and to the period 2000–2020, while the first [44] was a global review covering the period from 1982 to mid-2018. Both reviews used as sources databases such as Agricola, ABI/INFORM and CAB [33], or search engines such as https://scholar.google.com/, www.getcited.org and http://academic.research.microsoft.com [44]. The strings used included "participatory plant breeding", "community breeding", "multi-actor breeding" [33], "participatory", "participation", "participatory research", "farmers' preferences", "plant breeding", "evolutionary plant breeding" and their combinations [44].

Both reviews included peer-reviewed papers as well as informal publications in order to capture projects described in the grey literature and online sources such as reports, proceedings and websites not included in peer-reviewed journals. The first paper did not include PVS, which was included in the global review, and only included projects which lasted at least three years. These two reviews outlined a number of findings.

The first one is the relatively large number of universities and national research institutions in the Global North, which are engaged in PPB programs even in crops where conventional breeding has been, and continues to be, commercially successful, by exploiting the advantages of hybrid cultivars such as brassicas, corn, chard, zucchini and tomato [33,45]. In these cases, PPB was adopted to respond to the request of organic farmers for a different type of variety to allow the production of their own seed, a frequent request made particularly by this category of farmers.

In the least developed countries, the use of PPB has been justified by the difficulties of centralized breeding to address the need of farmers practising agriculture in areas where the physical conditions were very different from those of the research station. The adoption of varieties by farmers in marginal areas has been, and continues to be, a problem [46,47]. The CGIAR is no exception, with a large number of varieties released but never adopted by farmers [48], arguably as a consequence, at least partly, of GEI.

The second finding emerging from these reviews is the high frequency of PPB projects, particularly in the Global North, addressing organic agriculture [33]. This is likely to be associated with the peculiarity of PPB to select predominantly for specific adaptation that suits the needs of organic agriculture, which, as a whole, represents a much more heterogenous population of target environments [49,50] than industrial agriculture. One additional reason is the increased demand by consumers for "niche" products, especially in terms of demand for organic food, locally grown products and traditional foods; and their concerns about standardized products, about too many "food miles" and the energy use of the supply chain [51]. This is associated with an increased willingness to pay for local products [52]. PPB has an advantage in addressing the diversified needs of farmers practising organic agriculture, who have limited access to varieties specifically developed to maximize performance in the absence of the chemical inputs available to industrial agriculture.

However, despite its successes, PPB has been institutionalized more often in universities than in breeding companies or public institutions with a specific plant breeding mandate.

The third finding is that PPB can easily be used with crops differing in mating systems, namely self-pollinated, cross-pollinated and vegetatively propagated crops of vegetables, root crops, pulses, and small grains. The crops most frequently used in PPB programs are rice, maize and beans, globally [44], and wheat, tomato and potato in the Global North [33]. There are also a few cases of PPB applied to fruit trees such as apple, pear [33] and chestnut [53].

The fourth finding is that PPB can easily accommodate underutilized crops for which the starting point of the program could be the genetic resources available in institutional gene banks and/or in farmers' seed banks.

6. Conclusions

Climate change requires a dynamic response with a rapid impact at farm level. The changes in the spectrum of pests, associated with changes in temperatures and rainfall, represent a challenge for centralized breeding programs, as these changes are expected to be location specific, representing at the same time a moving target. A breeding program based on decentralized selection offers the required dynamism because it is able to expose the breeding material to a range of target environments, including locations, years, agronomic managements and social contexts, and to rapidly switch to new ones when needed. Combined with the collaboration of users (farmers and other stakeholders), it increases the probability of adoption by considerably shortening the time from the scientists making a cross, to farmers growing a new variety in their own field [22,54]. Although PPB has been predominantly addressing organic systems, the increasing importance of climate change may imply that it could be useful also for conventional systems. In fact, biodiversity has been shown to increase the resilience of ecosystem productivity to climate extremes [55], which are expected to become more frequent [56].

The widespread use of inclusive client collaboration in plant breeding programs conducted by universities, and addressing organic agriculture, suggests that the lack of a more generalized institutionalization of PPB, particularly in the public sector, is not related to scientific issues. The most likely reason is that a breeding program, which favours specific adaptation, such as PPB, cannot be supported by large, centralized seed systems such as those managed by the few corporations that control the majority of the seed market today [57]. This implies that, most likely, the major obstacle to mainstreaming PPB is that the agrobiodiversity it creates in space and time requires a diffuse seed system made by small companies, possibly organized in partnership with the farmers themselves. Such a system does not lend itself to a centralized control.

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