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Section 1
General Topics Related to Organic Plant Breeding

1 Organic Crop Breeding: Integrating Organic Agricultural Approaches and Traditional and Modern Plant Breeding Methods

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Introduction

Organic agriculture is continuously growing worldwide on land and farms in more than 160 countries as well as in the global marketplace (Willer and Kilcher, 2011). Globally, there are 37.2 million hectares of organic agricultural land (including in-conversion or transition hectarage), which is about 0.9% of all arable lands. Of the total organic area in 2009, most (24.9%) is in Europe, followed by Latin America (23.0%), Asia (9.6%), North America (7.1%), and Africa (2.8%). Some individual countries (mainly those in Europe) had higher percentages due to support by national policies, e.g., Austria (18.5%), Sweden (12.6%), and Italy (9.0%; Willer and Kilcher, 2011).

Organic agriculture has its origins in the early 1900s with individuals advocating that “living soil” was a fundamental value of sound agriculture (Balfour, 1943; Howard, 1940; Pfeiffer, 1947; Steiner, 1958; Rodale, 1961). It was not until the 1970s that the organic movement grew substantially, however. Growth of the movement coincided with consumers’ and farmers’ reactions against the unsustainable environmental impact of the agriculture of that time. In the 1990s, organic agriculture became large enough to attract the interest of major food suppliers. In 2008–2009 organic products occupied about 5% of the market and were worth 55 billion US dollars, or 40 billion euros (Willer and Kilcher, 2011). To date, increasing development in the organic sector is influenced by three main drivers: *Values* (see four basic principles of the International Federation for Organic Agricultural Movements in Chapter 7), *protest* (promoting organic agriculture as an alternative strategy) and *market* (an economic interesting niche market). Alrøe and Noe, 2008.

Regulations translating the values and principles of the organic sector into rules and standards (IFOAM, 2005; Luttikholt, 2007) have been harmonized to promote global trade. The four basic principles of the organic movements as described by the world umbrella organization IFOAM, include (a) *the principle of health:* Expressing the concept of wholeness and integrity of living systems and supporting their immunity, resilience, and sustainability; (b) *the principle of ecology:* Promoting diversity in site-specific ecological production systems; (c) *the principle of fairness:* Serving equity, respect, justice, and stewardship of the shared world; and (d) *the principle*

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of care: Enhancing efficiency and productivity in a precautionary and responsible way (IFOAM, 2005; Luttikholt, 2007).

These principles have been codified in governmental regulations such as the National Organic Program (NOP) in the United States (USDA, 2002) and in Europe by the European Commission (EC, 2007).

It was only in the early 1990s that crop breeding and seed production came to the fore as an issue for organic growers and consumers in response to the emerging field of genetic engineering (GE) and strengthening of intellectual property rights. The organic sector began to discuss ways to actively stimulate crop improvement to meet organic principles.

In this chapter we will describe how organic management differs from conventional agricultural management, what plant traits are required for optimal adaptation to organic farming systems, and ways to acquire such adaptation via cultivar selection, seed production, and breeding. We also summarize the history and future perspectives for organic crop breeding in the United States and Europe.

How Different Are Organic Farming Systems?

When the U.S. National Organic Standards Board convened to advise the USDA on developing organic regulations, they described organic agriculture as:

> “. . . an ecological production management system that promotes and enhances biodiversity, biological cycles, and soil biological activity. It is based on minimal use of off-farm inputs and on management practices that restore, maintain, and enhance ecological harmony” (USDA, 2002).

Organic farming is more than merely replacing chemical pesticides and fertilizers with organic ones. Emanating from the principles of health and ecology, the aim has been to move away from curative measures and to amplify agro-ecological system resilience by developing preventative strategies at the system level (e.g., Kristiansen et al., 2006; see table 1.1). The goal is to stimulate a high level of internal system self-regulation through functional diversity in and above the soil, as opposed to depending on external inputs for regulation (Østergård et al., 2009).

In considering differences among current farming systems in Western societies (e.g., conventional with high-external inputs systems, conventional systems reducing external inputs to become more sustainable, and organic farming systems) organic farming systems are the most extreme of the three types in refraining from chemical-synthetic inputs and in using preventative rather than curative measures. Although conventional low-external input farming seeking sustainability can be considered an intermediate between high-external input farming and organic farming, there is still a critical difference. It aims to reduce the input levels through precision farming methods and integrated pest management but still relies on chemical inputs to quickly correct during crop growth. In contrast, organic farming systems that cannot (easily) “escape” by applying curative methods rely on indirect, long-term strategies of fostering systems resilience. Organic farming systems focus on soil building through increasing organic matter, which increases water holding capacity and buffers against perturbations to the system. Such systems generally lack short-term controls (e.g., by applying mineral fertilizers with ready water-soluble nutrients or pesticides) to modify the growing environment during the season. Because organic farmers have fewer means to mitigate environmental variation, the varieties grown in organic agriculture will exhibit larger genotype by

Table 1.1 Overview of the main difference in crop management between conventional agriculture, sustainable low-external input farming systems and organic farming systems

Category	Conventional Farming System	Sustainable, Low-External Input Farming Systems	Organic Farming Systems
Biodiversity	Not a specific issue	Attention given to natural predators	Biodiversity is both product of and tool for maintaining a resilient farming system. Including diversity in (beneficial) soil organisms, crop species, and varietal diversity in space and time
Fertilization	Application of high inputs of mineral nutrients, including hydroponics systems; aiming at maximum crop growth with readily soluble nutrients	Application of reduced levels of mineral fertilizers, precision fertilization, including use of green manures; aiming at optimal crop growth with reduced loss of nutrients by leaching	Application of reduced levels of organic fertilizers (animal manure, compost and green manures); slow release of nutrients; aiming at long-term soil fertility and high biological soil activity
Rotation	1:1 to 1:3	1:1 to 1:4	1:6 to 1:10
Crop protection	Highly dependent on synthetic-chemical crop protectants	IPM approach to crop protection. Scouting, and trapping; reduced application of synthetic-chemicals added with biological agents	Access to only organically approved inputs
Weed management	Herbicides	Reduced herbicide use and mechanical weeding	Mechanical weeding combined with crop rotation design, or no tillage systems including mulching; stale seedbed, and crop competition
Seed treatment and sprouting inhibitors	Chemical	Chemical and physical	Physical (hot water or steam) and organic additives, e.g., mustard powder
Tillage	Increasing use of no-till in major field crops	Application of minimum or no-till	Reliance on tillage but seeking to apply minimum- or no-till systems to field crops

environment interactions, with greater emphasis placed on cultivar traits that allow adaptation to variable growing conditions (Lammerts van Bueren et al., 2007).

Another important difference among the aforementioned farming systems is that the main source of nitrogen (N) in organic farming systems is mineralization of organic matter, making N availability less controllable (Mäder et al., 2002). Under low temperatures in spring, soil microbiota that mineralize organic matter are not active enough to provide sufficient N, causing crop growth to lag and allowing weeds to compete. This requires cultivars that can cope with early season low fertility and produce vigorous growth to cover the soil as early as possible.

Consequences for Cultivar Requirements

A conclusion drawn from the description in the previous section is that conventional agriculture has more external means to adapt the environment to optimal crop growth, whereas organic farming systems need cultivars to adapt to the given environment. Crops bred for conventional production may be adapted to a narrower range of environmental conditions, especially those controlled by the external inputs of the grower. Therefore, cultivar selection is more critical for organic than for conventional farmers. The emphasis is on choosing flexible, robust cultivars that are adapted to such farming systems and that possess yield stability and can compensate for unfavorable conditions.

Organic growers have largely depended on cultivars bred for conventional systems, but not all are optimal for organic farming systems because traits associated with independence from external inputs have not received high priority in current breeding programs.

Traits

A focus on breeding for organic agriculture would require a shift from emphasis on maximizing the yield level in combination with the use of "crop protectants" to an emphasis on optimal yield stability. One of the main characteristics of organic farming is a multilevel approach to increasing system stability to reduce risk of failures. A similar approach could apply to cultivar development to adapt to less controllable and unfavorable growing conditions (see table 1.2). The aim would then not only be adaptation to low nutrient levels supported by improved interaction with beneficial soil mycorrhizae, but also morphological and phytochemical traits that reduce disease susceptibility (wax layers in *Brassica* species, open plant architecture), enhance weed competition (early vigor and planophile growth habit), and increase in flavonoids and glucosinolates (pest feeding deterrents; Stamp, 2003; Züst et al., 2011).

From Cultivar Evaluation to Organic Seed Production and Plant Breeding Programs

Just as conventional colleagues do, organic farmers are always looking for the best cultivars to meet their needs. As described above, cultivar choice is a valuable tool of organic farmers to increase system and yield stability. Many research projects have emphasized farmer participatory trials to evaluate current cultivars to select the best performing cultivars under organic growing conditions. The next step in evolution to an organically based breeding program has been to produce organic seed of the most suitable conventionally bred cultivars. The subsequent step has been to identify "ecological" traits that should be included in current breeding programs. Often breeders interested in breeding for low-input or organic farming have also found that the protocols for cultivar testing need to be adapted to allow appropriate cultivars to enter the market (e.g., as in Europe; Löschenberger et al., 2008; Rey et al., 2008; see Chapter 8).

The final step in program evolution has been to develop appropriate cultivars through breeding programs that are conducted under organic conditions. Table 1.3 shows an overview of such steps that currently coexist in the market. These steps represent a continuum that, depending on the goals of the breeding program, may fall somewhere in between. For example, rather than maintaining two distinct programs for conventional and organic, some private companies do their early breeding in conventionally managed environments, then test later generations in both conventional and organic trials (Löschenberger et al., 2008).

Organic Seed Production

Crucial to engaging breeding companies to in breeding better adapted cultivars is stimulating organic seed production of the best performing cultivars. Even before organic breeding became an issue,

Table 1.2 Differences in plant ideotype between high input conventional and low-input organic cropping systems

Conventional	Organic
Above-ground traits	
Performs well at high population density	Optimal performance at lower densities
Increased harvest index	Increased harvest index, but not as dramatic as for conventional production
Erect architecture and leaves, shortened plant stature	Taller plants, spreading canopy to be productive in low input situations
Weeds controlled by herbicides	Weeds limited by competition (plant height, spreading architecture), plants tolerate cultivation
Yield is maximized with high level of inputs	Maximized sustainable yield achievable with input of nutrients from organic sources
Pest and disease resistance to specific complex of organisms; need for resistance to diseases of monoculture systems	Pests and pathogens of monoculture potentially less severe, pathogen and pest complex differ; induced resistance relatively important; secondary plant compounds important for pathogen and pest defense
Rhizosphere traits	
Root architecture unknown	Exploratory root architecture; able to penetrate to lower soil horizons
Adapted to nutrients in readily available form	Adapted to nutrients from mineralization – not readily available; need for nutrient use efficiency; responsive to mycorrhizae
Legume-specific traits	
Nitrogen production by rhizobia of lesser importance	Rhizobia more important; discrimination against infective rhizobia important for N acquisition
Harvest and marketing traits	
Improved labor efficiency	Incorporate traits that improve working conditions
Improved processing, packing, and shipping efficiency	Improved nutrition, taste, aroma, and texture
Crop shaped by mechanical harvest constraints	Traits priorities set jointly by researcher and farmer

Table 1.3 Time schedule to develop organic seed production and plant breeding

Time	Activity	Product
Current	Selection of best-performing conventionally bred cultivars; No use of GM cultivars	Conventionally bred cultivars
	No chemical post-harvest seed treatments	Conventionally produced, untreated seeds
Short-term	Organic seed production of the best suitable conventionally bred cultivars	Conventionally bred cultivars
	Organic seed treatments	Organic seed production
Mid-term	Including “ecological” plant traits in conventional breeding programs	Low-input cultivars
	Adapted protocols for organic variety trialing (e.g., VCU) to allow adapted cultivars to pass testing thresholds	Organic seed production
Long-term	Whole breeding cycle under organic conditions	Organically bred cultivars
	Including the concept of integrity of plants	Organic seed production

organic seed production (free of pre- and post-harvest chemicals) had already started to develop on a small scale in the 1970s. This was mainly driven by small enterprises concerned about lost genetic diversity that had once preserved older heirloom and regional varieties. With more stringent rules on the use of organic seed incorporated into organic regulations in the United States and the Europe Union, the conventional seed industry became interested in serving this market. As a result, the availability and use of certified organic seed has increased and seed businesses have matured. Both small organic enterprises and larger commercial companies (who have traditionally only serviced conventional markets) are dealing with organic seed production of both horticultural and field crops.

At present, one can generally distinguish four types of organic seed production businesses:

- Fully organic and independent seed companies;
- More or less independent daughter seed companies linked through formal partnerships to conventional seed companies;
- An integrated part of a conventional seed companies;
- Conventional seed companies that chooses not to produce organic seed.

Confronted with a limited assortment of suitable cultivars, organic growers have become more aware of the need for greater cultivar choice with a greater diversity in cultivar types (e.g., open-pollinated, F_1 hybrids, or variety mixtures). In this context, organic crop breeding has become an emergent sector in business and science.

The History of Organic Crop Breeding in Europe and the United States

Breeding activities for organic agriculture in Europe and the United States have had distinctive historical trajectories that are products of different laws and policies concerning seeds and plant breeding.

Europe

In Europe, plant breeding within the organic sector started in the 1950s on a small scale conducted mostly by biodynamic farmers considering selection as part of their farming system. They felt that it was imperative to allow cultivars to co-evolve over time into more resilient farm organisms (e.g., Kunz and Karutz, 1991). In that context Martin and Georg Schmidt developed (“regenerated”) winter rye through the ear-bed method by sowing the kernels according the position in the ears and developing a procedure for selection resulting in a very tall (2 m) winter rye cultivar named ‘Schmidt Roggen’ (Wistinghausen, 1967). In the 1980s a biodynamic working group of farmer breeders and specialized breeders/researchers met in Dornach, Switzerland, to discuss several research methodologies. In 1985 a group was formed in Germany (“Initiative Kreiz”) that led to the founding of Kultursaat in 1994, which is an association for biodynamic breeding research and maintenance of cultivated species (see www.kultursaat.org; Fleck, 2009). This group now consists of approximately 40 breeders and farmer-breeders, each improving one or more crop species in the context of a biodynamic farm. They currently have registered about 40 new vegetable cultivars. Kultursaat considers breeding to be a public activity and the group is supported financially by donors and seed funds. The seed production of these new cultivars and older open-pollinated and heirloom varieties is organized by the company Bingenheimer Saatgut AG in Germany. In addition to vegetable breeders, several biodynamic cereal breeders began programs in the mid-1980s in Germany and Switzerland (e.g., Kunz and Karutz, 1991; Müller et al., 2000).

Toward the end of the 1990s, broader support emerged to address gaps in improving cultivars for organic farming systems, and breeding research was initiated by organic research institutes and universities in Europe, which were funded on a project basis by national governments and as European cross-country consortia: For example, a large-scale collaborative breeding project SOLIBAM from 2010–2015 for several crops (www.solibam.eu).

To stimulate knowledge exchange on breeding for organic agriculture, a European Consortium for Organic Plant Breeding (ECO-PB) was founded in 2001. Among other functions, it has organized several conferences (see www.eco-pb.org) to provide a venue for information exchange. ECO-PB acts as an umbrella organization that supports harmonization of the national organic seed regimes by organizing roundtable and workshop meetings on the issue (e.g., Lammerts van Bueren and Wilbois, 2008).

Increasing numbers of conventional breeders became interested in breeding for the organic sector. Not only was there a need to serve this growing market, but they also saw it as an investment in breeding for the future, as conventional agriculture moves toward increasing sustainability. During the Eucarpia Conference on Breeding for Organic and Low-input Agriculture in 2007 in Wageningen, the European Association of Plant Breeders and Researchers (Eucarpia) founded the Section "Organic and Low-input Agriculture" (www.eucarpia.org). To support publishing of peer-reviewed results, a special issue of Euphytica was published in 2008 (Lammerts van Bueren et al., 2008). Also the Proceedings of the Second Conference of the Eucarpia Section Organic and Low-input Agriculture revealed many research projects aimed at improved selection methods or strategies for organic plant breeding (Goldringer et al., 2010). In addition to the fact that several European universities have various research programs set up to develop methods to obtain adapted varieties, Wageningen University in the Netherlands initiated an endowed chair specialized in Organic Plant Breeding in 2005. Kassel University in Germany established a full-time chair for Organic Plant Breeding and Biodiversity in 2011.

United States

Origins of organic plant breeding in the United States are not well documented. The emergence of organic organizations came about in the 1970s, and around the same time, seed companies and nonprofit organizations (NGOs) with an interest in seeds arose (Dillon and Hubbard, 2011).

While little is known about the varieties in use by the early practitioners of organic agriculture in the United States, most were almost certainly non-hybrid, open-pollinated (OP) heirloom varieties. The early seed companies were selling predominantly OP varieties to organic growers, and NGOs such as Abundant Life and Seed Saver's Exchange were focused primarily on preserving heirlooms as a counter to the loss of biodiversity that was beginning in the formal seed sector. The use of OPs and heirlooms was tied to environmental, economic, and social sustainability values and was a reaction against what organic practitioners saw happening in the conventional seed industry. The ability to save OP seed fit well with the "back to the land" movement of the 1970s, which embraced organic agriculture and had a strong belief in self-reliance. With the exception of field corn, where most varieties offered commercially are F_1 hybrid, catalogs selling organic seed carry proportionally more OPs than F_1 hybrids (Dillon and Hubbard, 2011).

The Organic Food Production Act passed in the 1990 farm bill gave the federal government the authority to craft a national organic standard. This resulted in the publication of the National Organic Program (NOP) in 2000, and after receiving feedback from stakeholders, the program was implemented by USDA in 2002. It was apparent from the beginning that access to certified organic seed was a limitation, as apparent in the NOP advisory on certified organic seed which states "The producer must use organically grown seeds . . . except . . . non-organically produced, untreated seeds and planting stock may be used to produce an organic crop when an equivalent organically produced variety is not commercially available" (USDA, 2002). This exception was instituted because certifying agencies and regulators recognized that the organic seed market was not large enough to supply the needs of the organic sector, and that many organic growers relied on conventional sources for their seed needs. Over time, this loophole shrunk. In 2010, certification inspectors were requiring that a grower check at least three seed sources to determine if their desired variety or equivalent was available as certified organic seed. If not, then the grower was allowed to use untreated conventionally grown seed. Much of the recent surge in plant breeding and trialing activities have sought to increase the portfolio of varieties available to growers in organic form.

Organic plant breeding activities by the private sector are not well documented, but probably began in the 1970s or 1980s on the part of companies that were selling organic seed. Organic plant breeding in the public sector was formalized in the mid-1990s with funding from federal grant programs such as the USDA Sustainable Agriculture Research and Education program (SARE), federal Risk Management Agency (RMA), USDA Value Added Producer Grants program (VAPG), and USDA Integrated Organic Program (IOP), which later became the Organic Research and Education Initiative (OREI). NGO organizations funding organic research included the Organic Farming Research Foundation (OFRF) and the Farmers Advocating for Organics fund (FAFO). At least 57 projects were funded through these venues from the mid-1990s to 2010 (Dillon and Hubbard, 2011). Funding has been distributed to both field and vegetable crops with the majority going to wheat and vegetables. Over this time period approximately $9.1 million (€6.3 million) has been invested with most of it administered recently through USDA OREI grants. A large part of these projects has been a farmer participatory component. One of the most difficult aspects of this funding is that it has typically been for a year or a few years at a time, preventing continuity in programs that generally require a decade to develop. It is only recently that varieties from the first programs have been released and the number is expected to grow.

Organization of meetings for information exchange has been relatively recent in the United States. Among the first sponsored by the American Society of Agronomy, Crop Science Society of America, Soil Science Society of America (ASA-CSSA-SSSA) was an Organic Symposium in 2003 (Podoll, 2009). Another Organic Symposium was conducted as part of the 2005 Annual Meeting was about "Organic Seed Production and Breeding for Organic Production Systems." In 2007, the American Society of Horticultural Sciences Annual Meeting sponsored a colloquium on "Breeding Horticultural Crops for Sustainable and Organic Production." Regional meetings, such as Organicology in the Pacific Northwest, Ecofarm in California, MOSES in Wisconsin, and the NOFA conferences in the North east have all had plant breeding and seed components.

Comparison of European and U.S. Experiences

One of the obstacles to European organic breeding efforts has been the registration requirement for any variety in commercial trade (see also Chapter 8). The same obstacle has not been present in the United States, where growers have had freer access to older traditional varieties. This has perhaps caused the U.S. breeding effort to lag behind that of Europe because there has not been the regulatory-driven need to breed new varieties. In general, the European organic breeding effort has been ahead of the U.S. effort, when the first breeding efforts took place, in the organization of conferences, and in establishing chairs of organic breeding at public institutions.

Funding for organic breeding is roughly similar on both sides of the Atlantic. Given the limited information available, it is difficult to compare European and U.S. private sector efforts, but European companies have invested more heavily than U.S. companies, and in fact, some of the largest organic seed companies in the U.S. are European based.

Since the late nineteenth century, the U.S. has strongly supported public plant breeding through the land-grant university system. However, in the last two decades, the ranks of public plant breeders have declined. Some of this has come about by reduced federal funding to support these positions, and some have been converted into biotechnology positions. Another source of pressure on public plant breeding has been strengthening the private sector through the advent of stronger intellectual property rights. As private companies have taken over plant breeding efforts in many crops, there has been less of a need for public plant breeders in those crops, with a subsequent increase in the difficulty for public plant breeders to obtain operating funds for their research. One consequence of the loss of public plant breeders has been fewer graduate students trained in plant breeding, which has alarmed private seed companies because they do not see where their future cadre of plant breeders will come from (Ransom et al., 2006).

With the increase in funding for organic research in general, and plant breeding in particular, a niche has been created where public plant breeders can operate. Because private seed companies are reluctant to invest in organic plant breeding, public breeders can conduct research programs on crops that would otherwise be the domain of the private sector for traits of importance to organic production (and ultimately sustainable agriculture). At the same time, these types of projects provide a venue for training the next generation of plant breeders.

Perspectives and Challenges for Breeding for Organic Agriculture

Although organic seed production is increasing annually, specific organic breeding programs are few, and many are focused on cereals.

Currently three types of breeding programs are operating (Wolfe et al., 2008):

a. Conventional breeding programs resulting in cultivars (by chance) also suitable for organic farming systems;
b. Conventional breeding programs aimed at cultivars adapted to low-input and organic agriculture;
c. Organic breeding programs fully conducted under organic growing conditions.

The organic sector is too small to financially support enough programs to improve a wide range of crops, so the reality is that these three types of programs will run in parallel for at least the next two decades (Osman et al., 2007). Another model calls for cooperation of organic breeding programs with conventional breeding companies and institutes that recognize the need for sustainability – and who anticipate developing societal recognition from the contribution that breeding for low-input and organic agriculture can make.

The challenges for research to support the development of breeding for organic farming systems focus on the following three categories:

a. Defining which selection criteria are relevant per crop;
b. Defining selection methods;
c. Developing appropriate socio-economic and legal conditions to stimulate organic breeding programs.

In many regards, organic production is still a black box, in terms of knowing what traits are important for adapting a cultivar to an organic system. We know in general terms what conditions are limiting, but what the optimal plant traits might be is open to investigation. An example would be phosphorus use efficiency, which can be achieved through mychorrizal symbioses or through developing vigorous root systems that are better at exploring the soil. Both approaches have advantages and tradeoffs, and it is not yet possible to know which is better for a particular situation.

There is a need to design more efficient breeding methods for organically adapted crops. Farmer participatory methods have been used in organic plant breeding because when working in a new system, breeders do not always know what traits are important to growers. Farmer participatory methods can work quite well, especially in situations that empower farmers and lead them to take over breeding activities, but they have drawbacks in terms of resources required to visit the sites or bring farmers to a central site. There is also a need for breeding methods that can work around techniques or traits that are considered not compatible with organic principles. Examples include cytoplasmic male sterility derived through somatic hybridization and disease resistances developed with the aid of embryo culture.

The socio-economic, policy, and legal frameworks to facilitate organic production are currently lacking. The increasing use of utility patents to protect crop varieties (in the United States) and methods (both in Europe and the United States) are limiting germplasm exchange and thereby reducing the rate of genetic progress. The variety registration system in Europe has difficulties in coping with the heterogeneous materials developed by organic plant breeders who seek diversity in their varieties.

Conclusion

Organic crop breeding is rising from its infancy, has been maturing as a business, and is becoming a scientific discipline. It is contributing not only to the needs of organic farmers who require cultivars better adapted to their farming systems, but also to the development of sustainable agriculture aiming to reduce external inputs. Organic crop breeding is an essential strategy in arriving at such sustainable farming systems.

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