1.3 Advanced technologies impacting the green development of seed industries

Mauricio Antonio Lopes
Brazilian Agricultural Research Corporation (Embrapa), Brasilia, Brazil

Abstract

The agriculture of the future will be impacted by concepts, methods and expectations far beyond conventional agricultural systems. The Sustainable Development Goals (SDGs) point strongly to the need of agriculture and related industries to embrace new practices and new criteria of performance, with more balanced attention to the three dimensions of sustainability – economic, social and environmental. The good news is that the technological standards of agriculture are being changed by the introduction of fast-paced advances in scientific knowledge. Scientific revolutions are happening in biology with genomics, in physics and chemistry with nanotechnology, in information technology and communication, with numerous innovations that increase our ability to respond to risks and challenges. Considering these advances and the gradual emergence of a cleaner, decarbonized, green economy, the expectation is that agriculture´s important domains, such as plant breeding, cultivar development and their related seed industry will be faced with a new set of standards and requirements, and increasing expectations for innovations to lower impact and drive food systems towards a sustainable future.

Introduction

A few years back, Klaus Schwab, founder of the World Economic Forum, analysing the accelerated scientific and technological development of our time, concluded that "we live in a time of great promise and great peril" (Schwab, 2016). According to him, this time of rapid changes and disruptions presses us to build a comprehensive and globally shared vision of how technology is affecting our lives and reshaping economic, social, cultural and human environments. The warning is prudent considering, for example, the emergence of mega-corporations accumulating enormous power, the radical changes in the world of work, the impact of technology on human relations, among other risks (WEF, 2022).

The warning becomes even more important now, with the world taking the first steps in the era of exponential technologies, which reveal capacity and reach many times multiplied, in increasingly shorter time frames and at ever-lower costs. Humans are incrementalists by nature, whereas technology increasingly is exponential. Thus, future changes, which are being led by new groundbreaking technologies, should be viewed as exponential and different from the incremental changes of yesterday (Harrington, 2018). A classic example of exponential technological advancement is the famous Moore's Law, based on a 1965 prediction that turned out to be true: that the processing power of computers would double every 18 months (Schaller, 1997). Since then, the rapid development of digital technologies has promoted enormous evolution of processes, competencies and business models, changes that will reach new levels with the emergence of artificial intelligence and quantum computing (Ayoade, Rivas and Orduz, 2022; Choi, Oh and Kim, 2020).

Digital transformation creates solutions that can operate in synergy or in "cross-fertilization", accelerating technological leaps that characterize the exponential progress we have already experienced with social media, e-commerce, the internet of things, artificial intelligence, robotics, etc. (Davidovski, 2018) – exponential innovations that will amplify their reach and impact with the inevitable explosion of connectivity (Langley *et al.*, 2021). As of January 2021, there were 4.66 billion active internet users worldwide – 59.5 percent of the global population. Of this total, 92.6 percent (4.32 billion) accessed the internet via mobile devices (Johnson, 2021).

This scenario of radical changes foreshadows numerous advances, but also many dangers, as Klaus Schwab warns (Schwab, 2016). As technology advances at exponential rates, institutions – particularly public ones – adapt at much slower rates (Hanna, 2018). How to reconcile capacity and action to respond to challenges at the frontier of knowledge, with capacity and action to broadly guarantee the most basic rights of populations, such as housing, education, health and security? It is probable that traditional governments, operating structures with limited coordination and synergy, will be incapable of understanding the emerging reality and, therefore, be less able to offer answers to the complex challenges ahead (Mazzucato, 2013).

Furthermore, in the face of the constant and faster evolution of science and technology, more innovations will emerge, and the gaps will tend to get wider and wider. Citizens with easy access to information and knowledge, disseminated massively through digital media, will become more enlightened, engaged and demanding. New business standards will emerge, incorporating concepts, tools and practices of management and governance, which makes the private world more demanding for governments, in their executive and structuring role, or in their role of formulating and improving appropriate public policies (Mazzucato, 2013; Stiglitz and Greenwold, 2014).

It is not enough to say that an era of exponential advances calls for governments capable of incorporating technologies and work models that are also exponential, with adjustments in skills, infrastructure and coordination (Hanna, 2018). A new workforce that is agile and adaptable to continuous change will need to be formed (Bongomin *et al.*, 2020). Working with citizens and engaging communities will be imperative to capture signals, cooperate and validate government actions. Infrastructure will suffer from high costs and rapid obsolescence. Therefore, eliminating redundancies, creating data standards and platforms, planning and shared projects will be mandatory changes (Hanna, 2018; Mazzucato, 2013).

This context of changes and challenges has many implications for food systems that are at the nexus that links food security, nutrition, human health, the viability of ecosystems, climate change and social justice (Caron *et al.*, 2018). To deal with food, environmental and social challenges in an age of fast technological changes and disruptions, countries will need to integrate data and information from public and private environments, carry out predictive and contextual analyses, guide policies, define performance goals and metrics – advances that can only be achieved with radical changes in structures, leadership and coordination.

Despite the huge success of agricultural research and innovation over the last century, current and emerging problems and crises will inevitably pressure the reinvention of agricultural systems, a challenge that will benefit from ever more abundant scientific advances. In an increasingly intensified, high-performance agriculture, a path to sustainability may be facilitated by the possibility to incorporate knowledge and technologies to manage more complex operations, involving rotation of different crops, wider choices of species and varieties, multiple methods of soil, water and fertility management, sophisticated risk management, among other challenges conducive to sustainable farming.

Progressive automation has immense potential to empower site-specific management methods and practices with gain in precision and efficiency in the use of inputs, in pest control and other operations. Under such circumstances, agronomic research in the future will have to deal with an increasing number of factors, requiring closer interaction with producers, whose areas will practically become fields of experimentation. With advances in information and communication technologies, agronomists will be able to access and process multiple combinations, in real time and in the real world of production, whether large, medium or small ventures, identifying combinations that are economically, environmentally and socially adequate for a given reality.

Another major challenge for agronomy and rural areas is the pressure for multifunctionality, in response to the 2030 Agenda and the SDGs (UN, 2015). Besides production of food and fibres, agriculture can also be a provider of renewable energy and biomass feedstocks to sustain cost-effective strategies to help decarbonize industries still dependent on non-renewable fossil sources, for production of energy, chemicals and materials. In addition, consumers are increasingly interested in new flavours and aromas, unique and memorable sensory experiences that shape culinary end products with enormous potential for social inclusion and wealth generation in rural areas.

In such a scenario, industries and businesses will have to evolve, integrating capacities and domains of knowledge to help empower agricultural systems and rural areas in the face of many forces and factors that will forge the agriculture and the food systems of the future (Schwoob *et al.*, 2018). The seed industry can be considered one of the most important, in this context, considering its enormous impact over the last century. Many modern agriculture successes are clearly associated to numerous biological innovations embodied in seeds. Unprecedented growth in crop yields began with the development of hybrid crops in the United States of America in the early part of the twentieth century, followed by the Green Revolution of the 1960s and early 1970s and, more recently, modern biotechnology, with game-changing innovations embarked in seeds.

This keynote address will analyse challenges for the seed industry, faced with a rapid development of new concepts, methods and advanced technologies and the emergence of a cleaner, decarbonized, circular, green economy, aligned to the SDGs. An industry faced with a new set of standards and requirements, and more expectations for solutions to help agriculture and food systems to move faster towards a sustainable future.

Technology increasing plant breeding capacity

Crop varieties are the foundations of civilization and, as such, have a sizeable impact on food security, economic and social stability around the globe. Plant breeding has provided a wealth of genetics-based solutions to help increase global food production, being a key driver for increased productivity in all agricultural sectors. It is consensus that the impressive growth in agricultural productivity and production over the last century was possible because farmers had a reliable source of good quality seeds of well-adapted varieties. Plant breeding, and the seed industry, made it possible for farmers to access a regular supply of seeds and planting materials with genetic potential to perform well, provided the availability of water, fertility, pest protection and adequate agronomic practices.

As such, plant breeding and the seed industry have provided extremely reliable technology solutions to meet increasing demands of an expanding global population. Take the advances in maize production in the United States of America over time, with initial progress made by the farmers themselves, who selected local open-pollinated cultivars adapted to diverse environments (Duvick, 2005a, 2005b). These initial gains soon, in the following cycles, became small and, sometimes, even null. After the discovery and introduction of hybrid maize, a significant jump in productivity became possible. Breeders rapidly learned the potential of inbred lines, that crossed, provided a burst of performance through heterosis. The advance led to substantial increases in crop productivity with double-cross and single-cross hybrids developed and disseminated over the decades, reaching yields considered impossible to achieve before hybrid vigour was discovered and managed (Crow, 1998).

Scientific plant breeding has also shown that plant genetic resources are the fuel for progress, allowing plant breeders to search for higher yield and adaptation to different environments and conditions through manipulation of genotypes and genes to meet the needs of farmers. The tropicalization of soybeans is one of the most successful examples of creative use of genetic variability with high impact in agriculture and food systems (Dall'Agnol, 2016). This species arrived in Brazil in 1882, remaining unknown for about seven decades. It gained some importance only in the 1960s, with production growing from

206 000 tonnes to 1 million tonnes in one decade, still restricted to the southern areas of the country, under environmental conditions more similar to the centre of origin of this species in Asia (Gazzoni and Dall'Agnol, 2018).

Until the mid-1970s, most of the soybean grown in Brazil came from the southern states. It was in the 1980s that the crop began to spread throughout central Brazil, a large tropical area of savannah known as Cerrado (Goodland, 1971). That was possible due to the development of cultivars well adapted to the low latitude of the region – varieties bred to be less sensitive to photoperiodic variations. Continuous investment in genetic resources characterization, breeding and cropping systems development allowed soybean to advance during the 1990s towards the centre-north of the country (around 10° south to 12° south) with further expansion occurring in the 2000s, further to the north (latitudes near 0° to 5° south or 5° north) (Cattelan and Dall'Agnol, 2018).

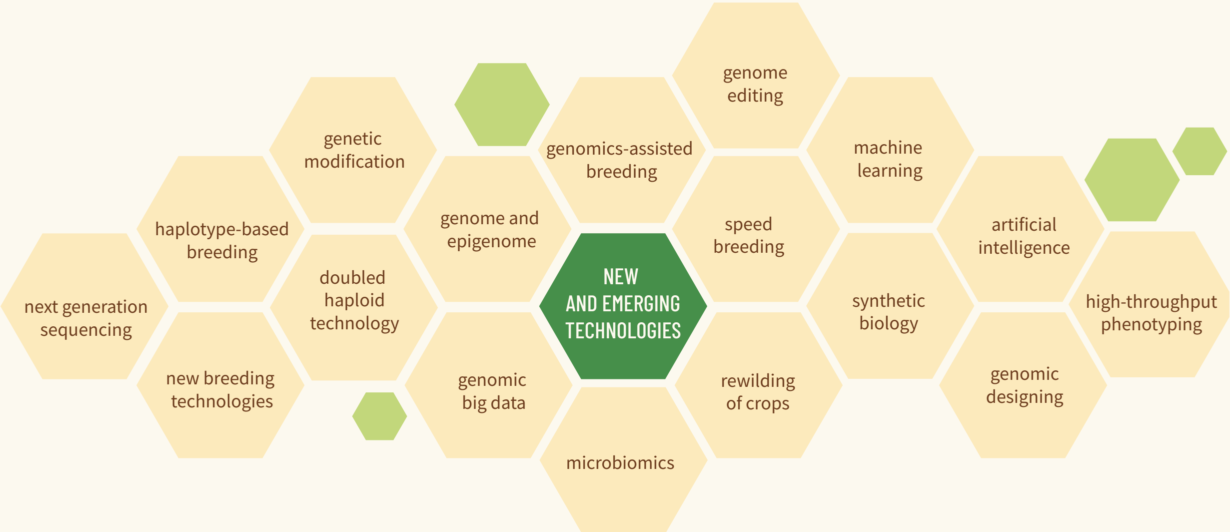
The expansion of soybean production in Brazil influenced expansion of other crops, especially maize, a preferred choice for rotation, with both crops accounting for more than 80 percent of the total area and 85 percent of the production of grains in the country. In the period 1990–2017, the total growth in production of these crops was significant – 313 percent against 76 percent increase in the farmed area (Embrapa, 2018) – an indication of substantial gains in agronomic performance, allowed by efficient access to genetic variability, to selection and breeding, together with improvement of agronomic practices. These advances strengthened food security, helping at the same time to transform Brazil into one of the major agricultural exporters in the world (Lopes and Martha Jr, 2014; Embrapa, 2014, 2018). The success of soybean and maize production in Brazil is an example of how investments in research and innovation were important to allow production in tropical areas considered marginal for centuries, like the Cerrado, with substantial impact in food security and economic progress (Martha Jr and Alves, 2018).

While conventional breeding approaches will no doubt remain a pillar of future crop improvement strategies, these will increasingly be augmented with the latest molecular innovations (Crisp *et al.*, 2022). Technological progress has driven down the price of plant genotyping assays and sequencing, which has translated into diverse methodologies available to breeders to accelerate improvement. These range from marker-assisted selection to genomic selection, underpinned by an explosion in available reference pangenomes and paired with advances in high-throughput phenotyping technologies (Hickey *et al.*, 2019; Varshney *et al.*, 2020; Bohra *et al.*, 2020; Steinwand and Ronald, 2020).

The tremendous impact of biotechnological developments we have seen in the past decades – such as transgenic technologies – were possible by building on knowledge and variability tailored by more than a century of traditional breeding and selection. Modern biotechnology associated with information technology and advanced instrumentation are giving us now a new wave of innovations capable of driving agricultural diversification, specialization and value aggregation, besides increased productivity, food safety and food quality well beyond any advances of the past (**Figure 1**).

Genome editing using clustered regularly interspaced short palindrome repeats (CRISPR)/ CRISPR-associated protein (CRISPR/Cas) technologies now offer efficient avenues to either create entirely novel alleles or to readily introduce rare or recalcitrant natural alleles into elite varieties. Initial applications have mostly focused on editing protein-coding regions within genes to knockout gene function. However, there is tremendous value in thinking beyond coding sequences, to tune the expression of genes and generate quantitative trait variation. We are gradually learning that factors beyond the coding sequence of genes contribute to trait variation in crops, and progress has been made in understanding the contributions of both epigenetic variation and cis-regulatory variation to plant traits. This non-genic variation has great potential in future breeding, synthetic biology and biotechnology applications (Crisp *et al.*, 2022).

Figure 1. New and emerging technologies influencing the capacity of seed industries to deliver solutions to farmers.



Beyond the wonders of biology and modern biotechnology, innovations in the fields of information technology and communications, remote sensing, advanced instrumentation, automation and robotics indicate that precision agriculture will emerge as common practice in agriculture in the near future, with potential impact in cultivar development and the configuration of seed industries. These tools and processes will allow smarter use of our natural resource base, ensuring more productivity, efficiency and sustainability in production systems. Nanotechnology, with innovations in the scale of the billionth of the metre, also promises to revolutionize the development of multiple products, processes and instruments. Advanced sensors will enable the monitoring of production systems with great precision, new materials and processes will allow development of machines and equipment that are more efficient, accurate and durable.

Using these advances in agriculture to confront the challenges ahead is strategic for the world, considering the need to supply food for a growing world population, at the same time fulfilling expectations for diversity, adequate nutrition and sustainability (IIASA, 2018; Sachs *et al.*, 2019).

A wide array of technological advances is needed to facilitate preservation of natural resources such as soil, water, forests and biodiversity. In addition, we need more research to mitigate effects of extreme weather events and to allow adaptation to new presumptive scenarios of biotic and abiotic stress intensification, as well as energy insecurity (Shukla *et al.*, eds, 2019). Plant breeding and seed systems are not detached from this reality. As challenges become more complex, the world will need greater diversity of genetic materials, readily available to farmers of different scales, in developed and developing countries.

Lastly, but not less important, it is crucial to be alert, informed and acquainted with current and emerging trends and changes in demands and expectations of modern society, especially in standards associated with the global development agenda (Rockström *et al.*, 2009; IIASA, 2018; Sachs *et al.*, 2019; Rockström *et al.*, 2020). The 2030 Agenda and the SDGs (UN, 2015) point strongly to the need of agriculture and related industries to embrace new practices and new criteria of performance, with more balanced attention to the three dimensions of sustainability – economic, social and environmental.

Plant breeding and seed systems in the emerging bioeconomy

Biodiversity and climate are central elements in the complex equation of civilization that has brought us to the present. Globalization, trade, the internet and the proliferation of air and sea routes cutting the globe in all directions (Khanna, 2016) allowed the world to use the planet's finite resources with increasing intensity, multiplying the human impact on the Earth´s natural resource base (Crutzen, 2002; Steffen, Crutzen and McNeill, 2007; Lewis and Maslin, 2015; Dodds, 2019; Subramanian, 2019). Together, climate change and loss of biodiversity could reduce ecosystem resilience and limit our ability to adapt to abrupt changes in natural systems, with threats to our food and agricultural systems, population health, trade and, ultimately, the world peace (IIASA, 2018; Sachs *et al.*, 2019).

These are among the reasons why sustainability has climbed to the very top of society's priority agenda (UN, 2015). The interest in sustainability grows stronger as society realizes the limits of the development model that relies on non-renewable resources (Rockström *et al.*, 2009; IIASA, 2018; Rockström *et al.*, 2020). As the population grows in number and consumption capacity, so does the perception that the economy must rely more on biologically based, recyclable, renewable – and hence more sustainable – resources. This is the foundation for the new bioeconomy, which has been ranking higher and higher on the agenda of governments and companies around the world (White House, 2012; El-Chichakli *et al.*, 2016; Bugge, Hansen and Klitkou, 2016).

This is the reason for the growing interest in low-carbon resource-saving technologies capable of promoting the sustainable intensification of land use and more sustainable agricultural production systems. There are challenges to be faced that demand technological sophistication for more resilient land use practices, with increasing provision of environmental and ecosystem services from agriculture, with waste reduction and recycling, restoration and conservation of water sources, reduction of greenhouse gas emissions, among others. Therefore, any consistent agenda for the future of plant breeding and seed systems must follow an integrative and systemic perspective, focusing on the nexus of different challenge areas, and in new ways to mobilize genetic variability to help drive sustainability in rural areas.

The emerging bioeconomy will become a source of many creative strategies to mobilize genetic diversity to help agriculture face the challenges ahead. More attention to research in genetic resources and crop breeding is paramount, to expand the variability base and to mobilize through improved seeds new biological functions capable to help agriculture fulfil its part in the pursuit of a sustainable future. Here are some challenges the agricultural research community will have to face, to assure that genetic diversity will be available, with the help of the seed industry, in pursuit of a much-needed food security for the world in the future:

Strengthening crop breeding capacity

The production of new, more-adapted, and productive crop varieties, a result of genetic improvement, is one of the main contributions of agricultural research to humanity. Plant breeders have been able to adapt plants to a wide range of agricultural areas around the world, to cropland with marked differences in soil and climate, intense biotic and abiotic stresses and diversified technology usage patterns. Thus, capacity to develop genetic innovations in the form of improved crop cultivars will continue to be fundamental to all countries, especially in the face of increasing challenges posed by climate change and stress intensification (Shukla *et al.*, eds, 2019). *Strengthening crop breeding capacity through efficient research in plant genetics and biotechnology will ensure that agriculture maintains the ability to respond to problems that may jeopardize food and nutritional security in the future.*

Sustainable use of water

Despite being the sector that already consumes most water, irrigated agriculture tends to grow in the future, due to climate change and more extreme weather events, especially droughts. In addition, the need to increase agricultural productivity to meet the demands of a growing population will increase concerns and conflicts related to competitive uses of water. Therefore, a major challenge for the future will be the optimization of water use by agriculture in order to reduce the pressure on this finite resource and release water for other purposes. Innovations to rationalize the use of water and to avoid or reduce its waste will be critical to meet the growing demand for food, with minimal environmental impacts. *Access to genetic variability and to biotechnological tools and processes to empower crop breeding will be essential to make crops increasingly more efficient in the use of water.*

More effective protection of agriculture

One of the critical challenges for food production is the movement of exotic organisms or invasive species from one region to another, depending on trade, transport and tourism. Globalization of pests leads to displacement of organisms from one region to another, intentionally or not, with significant potential for economic, environmental and social impacts. Strong emphasis on technological innovation is critical to meet the diverse demands of importing countries and respond to rigid compliance standards that are consolidated internationally. Countries will have to develop production systems sustained in sanitary practices consistent with internationally accepted patterns of quality and safety assurance for their agricultural products. *Availability of genetic resources and breeding research on plant resistance to pests will play an increasingly prominent role in the defense of agriculture around the world.*

Safety and efficiency of agricultural inputs

There is no doubt that farmers will be pressed to seek alternatives or substitutes for inputs of high environmental impact, especially those derived from non-renewable sources. Many conventional inputs, like pesticides and fertilizers, contribute to rising costs in food production, and may have deleterious impacts on the environment. It is, therefore, necessary to develop alternative and safer sources of nutrients, such as nitrogen fixation by bacteria or biorelease of phosphorus and potassium from non-conventional mineral sources. In addition, the research in genetic resources can contribute to identify variability to efficiency of nutrient use by plants, particularly those nutrients that are scarce or have large potential impact on the environment. *Crop breeding and biotechnology have the capacity to mobilize variability to increase plant resistance to pests and nutrient use efficiency, with high potential of impact in the sustainability of agriculture.*

Linking food, nutrition and health

The concerted integration of food, nutrition and health strategies appears to be inevitable, due to demographic changes (increase in the average age of the population) and the exhaustion of health and social security systems, even in developed countries. The gradual change to a disease prevention paradigm will require food more suited to the needs of consumers (biofortified with vitamins, minerals and high-quality protein), adapted to demographic changes (increasingly elderly population) and capable of boosting performance in various capacities (physical, intellectual, etc.). *Genetic improvement will have to focus on the development of food with high nutritional and functional density, high quality, producing minimal waste and enabling manufacture at low cost with high productivity.*

Sustainable intensification of land use

Technologies capable of allowing increased and more sustainable use of the natural resource base will receive more attention in the future. In many parts to the world, agricultural land has been degraded and abandoned. If recovered, these are the ideal areas for expansion of agriculture, livestock and planted forest, without the need for further deforestation. It makes more sense to recover degraded areas than to open forested areas to farming. Integrating production systems, like crop–livestock, and crop–livestock–forest are viable possibilities for land recovery in many countries, especially in the tropical belt of the world (Lopes, 2019). Such technological innovations may allow configurations of low-carbon agriculture and dissemination of sustainable and more resilient farming practices. *The research on genetic resources and breeding will contribute to development of plants and animal breeds better adapted to low-carbon agricultural systems based on crop–livestock and crop–livestock–forest integration.*

Precision agriculture
The implementation of site-specific management practices on farms has the potential to provoke a revolution in agriculture, for reasons that include: a) virtually all agricultural areas have significant spatial variability in factors that affect crop yields, such as fertility, humidity, pest dispersion etc.; b) today we have knowledge and tools to identify and measure multiple sources of variability; and c) with this knowledge, we can use information and communication technology tools, associated with advanced automation, to modify management practices in order to increase efficiency and reduce impacts. With recent advances in drone technologies, artificial intelligence, sophisticated algorithms, sensors and actuators, significant gains in precision, accuracy and sustainability will become possible, *possibly requiring modulations in plant structure, functions and performance, which must be provided by breeding, through improved seeds.*

Conclusions

The agriculture of the future will be impacted by concepts, methods and expectations far beyond conventional agricultural systems. The SDGs point strongly to the need of agriculture and related industries to embrace new practices and new criteria of performance, with more balanced attention to the three dimensions of sustainability – economic, social and environmental.

Humans have built a successful journey on the planet by observing natural systems and making interventions to adapt plants, animals and ecosystems to their needs. But, at various points in this trajectory, such interventions began to ignore critical balances, refined by millions of years of trial and error that ensured nature's resilience and durability. The disruption of such balances to create benefits of exclusively human interest, in ever-shorter terms, puts the health of the planet at risk and, in the limit, may compromise the very viability of society.

Therefore, agriculture and food systems are under pressure to align with principles that were perfected millions of years ago and encoded in living things and natural systems, long before human evolution and the creation of agriculture, industries, commerce or any other modern artifact. It is urgent that we seek to mimic nature in its ability to integrate complex systems, using resources efficiently, incorporating waste into useful processes and products, conserving soil and water, fixing more than emitting carbon, maximizing energy efficiency, among many other functions.

Fortunately, scientific revolutions are happening in biology, physics, chemistry, information technology and communication, advanced automation and precision processes with numerous innovations that increase our ability to respond to risks and challenges. Considering these advances and the emergence of a cleaner, decarbonized, circular green economy, the expectation is that key agricultural innovation domains, like plant breeding, cultivar development and related industries will be gradually reinvented.

They will be reinvented to facilitate our journey towards the much-desired sustainability, which is nothing more than the reconciliation between human systems and nature. For agriculture, and the seed industry, such reconciliation will depend on a review of the concept of performance, traditionally associated with the amount of food or raw materials produced in a given space and translated into economic gain. The world that calls for sustainability already demands more sophisticated measures of performance from agriculture, focused not only on physical production and profitability, but also on eco-efficiency, social benefits and ethically acceptable management practices, all embedded in its operations, processes and products.

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