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STRATEGIES TO INCREASE CROP YIELDS IN A CLIMATE CHANGE SCENARIO

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Abstract

The forecasted effects of climate change – higher average temperatures, more intense and frequent droughts, increasing scarcity of water for irrigation – will worsen the problem of stress-induced reduction of crop yields, especially in arid regions. Development of new crop cultivars with enhanced tolerance to drought and salinity is probably the most promising strategy to improve agricultural productivity and food production. Some recent examples predict that this goal will be achieved in the near future using both, traditional breeding (with the help of new biotechnological tools) and genetic engineering. A complementary strategy could be based on the domestication of wild species naturally tolerant to stress. Optimizing plant nutrition with new and improved fertilizers will also contribute to stress tolerance of our present crops, as more resources will be available to maintain growth while activating defense mechanisms. There is also an increasing interest in the so-called 'biostimulants', a disparate group of unrelated substances that enhance crop quality traits, nutrition efficiency and/or abiotic stress tolerance, also contributing to increased yields under stress conditions. Examples of all these strategies are presented and discussed.

***Key words**: biostimulants, drought, plant breeding, plant nutrition, salinity.*

INTRODUCTION

World population continues growing, albeit at a lower rate than some decades ago, and will reach ~9.3×10^9 people by 2050. According to FAO estimates, global agricultural production should increase about 60% over the 2005-2007 levels to meet the expected food demand (Alexandratos and Bruinsma, 2012). This goal, *a priori*, should not be too difficult to achieve if we consider that between 1960 and 2009 the world population more than doubled but, still, we were able to increase the average amount of food available to each human being on the planet, from 2200 Kcal/person/day to >2800 Kcal/person/day. This was possible due to huge increases in crop yields, as a consequence of scientific and technical advances in agriculture, including the development of new, more productive varieties of our major crops – which were the basis of the so-called 'green revolution' (GR) of the 1960s and 1970s (Borlaug and Dowswell, 2005) – together with the massive use of agrochemicals (pesticides, herbicides, chemical fertilizers), the mechanisation of labour and a large increase in the area of irrigated cropland. Yet, the GR had also negative effects, since the high yields of the modern crop cultivars are dependent on high-input, intensive production practices that are not sustainable. In addition, the GR has caused a large loss of genetic diversity: modern agriculture is base on a narrow range of crop species and cultivars and thousand of landraces, minor cultivars and local varieties have been lost forever (or, in some cases, are stored in seed banks). This decreases the opportunities to find new sources of variation to fight future challenges, for example, changes in environmental conditions.

From the mid 1990s, the large-scale cultivation of biotech (GM) crops provided an additional boost (much smaller) to food production, as the transgenic varieties of herbicide-tolerant (HT) and insect-resistant (IR) soybean, maize and rapeseed (and other minor GM crops) have higher average productivity than the corresponding conventional crops. However, GM plants do not solve the drawbacks and limitations of our present agricultural systems regarding their low biodiversity, high inputs requirements or sustainability issues, since genetic transformation is carried out on previously improved 'GR' varieties.

In any case, today there is enough food to feed everybody on earth although, obviously, this food is not well distributed (FAOSTAT, 2015). Food production, both total and *per capita*, is still growing but the growth rates have been decreasing during the last 30 years, so that, even with an even global distribution of the available food, this increase in food production will not be sufficient to cope with population growth.

CROP YIELDS AND CLIMATE CHANGE

The effects of global climate change, including an increase in average temperatures worldwide, and more frequent, longer and more intense extreme weather phenomena (droughts, 'heat waves', floods...) will further reduce crop yields by contributing to the spreading of desertification and increasing the level of environmental stress conditions affecting the plants growing in the fields.

Good quality water for irrigation will be an increasingly scarce resource, due in part to climate change (lower rainfall) but also to its use for human consumption or for the industry.

There is as well a growing demand for biofuels, which compete with food as they are obtained at present from food crops: oilseeds for biodiesel and cereals (mostly maize) for bioethanol.

Furthermore, the global area of arable land is continuously decreasing, mostly by a change in land use due for urban development, industry or tourism. Yet there are other factors, which are also dependent on climate change effects, contributing to the reduction in the land surface available for agriculture: the loss of rainfed cropland due to prolonged droughts and the loss of irrigated arable land due to secondary salinization of the soil. The latter is an increasing problem in areas cultivated under irrigation in arid and semiarid regions, which happen to be the most productive agricultural lands in the world, where more than 40% of the global food is produced although they represent less than 20% of the total cultivated land.

In addition, it is necessary to develop sustainable agricultural systems that will allow increasing food production without depletion of natural resources and further degradation of the environment (Fita et al., 2015).

WHAT CAN WE DO (AND NOT DO) TO INCREASE FOOD PRODUCTION?

It is obvious that the present circumstances do not allow using the strategies that were successful in the past to improve crop yields. We cannot significantly increase the area of arable land, since marginal soils are not cultivable with the present crop varieties and we should not destroy lands of high ecological value, such as rainforest. We cannot increase the area cultivated under irrigation since not enough water will be available. Furthermore, improving the productivity of our conventional crops by a large increase in the use of (toxic and contaminating) agrochemicals, such as chemical fertilisers, will not be sustainable.

Since transgenic crops provide higher yields than conventional crops, we could extend the relative area of cultivation of the present 'biotech' (GM) crop... except in those countries where they already represent a very high proportion (> 90%) of the corresponding crop; for example, for soybean, maize, rapeseed (and cotton) in the USA. Cultivation of already established, minor transgenic crops can be scaled-up, and new biotech crops can be introduced, some of which have been already approved by the corresponding regulatory bodies or are starting commercial production (e.g., Bt eggplant in Bangladesh, China's Bt rice and phytase-containing maize, or Brazil's virus-resistant beans) (ISAAA, 2016). GM crops will contribute to solve the problem of limited food availability in the near future, but on their own, they will not provide the solution to the problem, as their contribution to increased global yields will not be significant enough.

ABIOTIC STRESS AND CROP YIELDS

For all major crops, average yields are only a fraction of record yields, and these losses – with can vary between 50% and >80% of the record yield, depending on the species – are mostly due to environmental abiotic stress conditions affecting the plants in the field, especially to drought and soil salinity (Buchanan et al., 2000). Therefore, the most promising strategy to improve crop yields and to increase food production will be based on the development of drought and salt-tolerant varieties of our major crops. For this, all available methods should be applied: traditional breeding techniques, genetic engineering (and soon genome editing) to generate 'biotech' tolerant crops, and even domestication and breeding of wild species tolerant to harsh stress conditions in their natural habitats.

TRADITIONAL BREEDING OF ABIOTIC STRESS TOLERANCE

Conventional breeding to obtain plant varieties with enhanced tolerance to abiotic stresses, such as drought and salinity, is far more complicated than breeding for other traits – for example, for resistance to fungal or bacterial pathogens, a character often dependent on a single resistance gene. The major reason is that, in contrast to the example mentioned above, abiotic stress tolerance is a multigenic trait, controlled by many different genes that generate a continuous variation (QTL, 'quantitative trait loci'). In addition, it is not easy to select the characters that precisely define stress tolerance, as the mechanisms involved are different for different stresses and the phenotypic responses vary with the developmental stage of the plant within the same species. Moreover, in many cases, it is difficult to identify appropriate sources of genetic variability for specific breeding programs. Therefore, it seems logical that this approach has been generally unsuccessful in the past, except for a few specific examples.

Nowadays, the breeder has a wide array of available biotechnological tools which make the breeding process faster and much more efficient. These tools include, for example, 'marked assisted selection' (MAS), or 'next generation sequencing' (NGS) technologies, which allow the identification of very large numbers of molecular markers, the establishment of extremely high-density genetic maps, and facilitate the precise location and cloning of the QTLs. Moreover, microsatellites or 'simple sequence repeats' (SSR) and 'single nucleotide polymorphism', (SNP) markers, generated by NGS, are used for the simultaneous analysis of a large number of individual plants in high-throughput genotyping platforms.

In the last years, with help of these technological advances, several successful examples of crops cultivars with enhanced tolerance to abiotic stress, obtained by 'classical' breeding, have been reported. To give only a few examples, we can mention several maize hybrids with improved water stress tolerance obtained at CIMMYT, in Mexico (Ribaut and Ragot, 2006); the generation of a highly drought tolerant rice derived from Kalinga III (an indica rice variety), using Azucena (a drought-resistant japonica rice variety) as donor parent to improve root morphology (Steele, 2009); or a salt-tolerant durum wheat variety in which the Na^+ transporter *nax2* has been introgressed from the wheat ancestral relative *Triticum monococcum* (Munns et al., 2012).

GENETICALLY MODIFIED STRESS - TOLERANT CROPS

There are thousands of reported experiments in which the expression of different genes in transgenic plants resulted in the enhancement of the tolerance of the transgenic to different stress conditions, in a higher or lower degree. The selection of those genes has been generally based on their known participation in basic, conserved mechanisms of response to abiotic stress in plants, and including, for example, genes encoding ion transporters, enzymes of osmolyte biosynthesis pathways, antioxidant enzymes, splicing proteins, signal transduction proteins or transcription factors (see specific examples in Fita et al., 2015).

Despite the enormous amount of information accumulated over the last 30 years on this topic, and referring specifically to salt tolerance, the fact is that at present there is no commercial, salt-tolerant crop variety growing in the field, so that the usefulness of the aforementioned (and other) genes as biotechnological tools to improve the stress tolerance of transgenic plants has been questioned. The major problem is that the vast majority of those experiments have been carried out in the laboratory or the greenhouse, using model species – *Arabidopsis thaliana*, in most cases – and it is not clear if these results can be extended to crop species. Moreover, stress tolerance is seldom evaluated from an agronomic point of view, not considering that any improvement of tolerance is useless if the quality of the harvested product or the crop yield is significantly reduced. Nevertheless, more recent experiments (still with *Arabidopsis*) suggest that the controlled expression of some genes, only in the presence of the salt stress conditions and in particular cell types, may be the key to obtain a significant improvement of salinity tolerance in the transgenic (Møller et al., 2009). It is to be expected, therefore, that in the coming years commercial salt-tolerant GM crops will be available.

This approach has been more successful in the case of drought-tolerant biotech crops, and a GM maize variety with enhanced resistance to water deficit has been grown commercially since 2012. This variety was developed in collaboration by Monsanto and BASF and has been transformed with bacterial genes encoding RNA chaperon proteins (Castiglioni et al., 2008). Although the expected increments in yield were modest, the resistant crop performed quite well in summer 2012 in some US States affected by a strong drought that year. A lot of work is being invested to develop drought-resistant varieties of other major crops.

In any case, it is to be expected that commercial biotech crops tolerant to drought and high soil salinity will be available in the near future, significantly contributing to the much-needed increase in crop yield and food production.

DOMESTICATION OF WILD PLANTS NATURALLY TOLERANT TO STRESS

Although the vast majority of wild plants and all major crops are relatively sensitive to abiotic stress, a small percentage of wild species are adapted in nature to extremely harsh environmental conditions, growing in arid (xerophytes) or highly saline (halophytes) habitats. An alternative to the genetic improvement of salt and drought tolerance of conventional crops would be the domestications of some of these wild species: since they already possess the trait that is most important and most difficult to introduce, the stress tolerance, it should be relatively simple to improve other agronomic and commercial characteristics, such as selection of the best genotypes, uniformity of the harvested product, or elimination of anti-nutrients.

Special attention has been given to the possibility of developing a ‘saline agriculture’ based of highly salt-tolerant plants, the halophytes. This would allow growing food and feed crops (and also crops for fibre, for biofuels, other industrial uses, or as ornamentals) in saline soils where conventional crops cannot be cultivated; this would include both, naturally saline marginal land and salinized arable land. These crops could be irrigated with saline or brackish water, even with seawater. Therefore, ‘saline agriculture’ will not compete with our present conventional crop for these limited resources: fertile farmland and good-quality fresh water for irrigation.

Among the most promising halophytic species for saline agriculture, we can include species of the related genera *Salicornia* and *Sarcocornia*, traditionally used as vegetables (in salads, for example) in coastal regions, collected from natural populations to be self-consumed or sold in local markets. In addition, they are very rich in minerals, unsaturated fatty acids and antioxidant. These species have a great potential for commercial cultivation, as well as other taxa that can be developed as vegetable crops: *Aster tripolium* (also used as ornamental), *Plantago coronopus*, *Inula crithmoides*... and many others.

Other halophytes can be used as oilseed crops. A good example is *Sarcocornia bigelovii*, which can be grown with seawater irrigation and produce seed yields similar to conventional oilseed crops such as soybean. The seeds are very rich in oil and proteins, and the oil contains a high content of ‘healthy’ polyunsaturated fatty acids, especially linoleic acid (over 70%). In addition, the seed meal can be used as a protein supplement in fish and ruminant diets.

There are many other examples of halophytes representing potential crops for food, feed or industrial uses, but we should mention the specific case of quinoa, up to now the most successful (and known) example of this approach. Quinoa is not really a ‘new’ crop, but in fact a very old one, cultivated in the Andean region for thousands of years. However, since it has not been cultivated at a large scale, it has never been subjected to 'modern' breeding programs. The species shown several remarkable properties: different ecotypes are able to grow from sea level to almost 4000 m, it is extremely tolerant to several types of abiotic stress: frost, drought or salinity, withstanding even irrigation with sea water. The species is considered as a 'pseudocereal', with gluten-free seeds, rich in starch and high-quality protein containing all essential amino acids. The straw is at least as nutritious as the seeds and could be an excellent source for animal feed. Although large-scale cultivation of quinoa is still limited to South America, the crop has extended to many countries in the last years, with FAO support in many cases (see Fita et al., 2015, for more information on 'saline agriculture' and additional examples of potential 'halophytic crops').

COMPLEMENTARY STRATEGIES

In addition to the general approaches described in the previous sections, additional strategies can also contribute, even if only modesty, to the goal of improving crop yields. We could, for example, recover traditional crops and local varieties, now abandoned or cultivated at a small scale, which may be more stress-resistant that our present major crops, and could provide reasonable yields under conditions unfavourable for conventional crops.

It is also possible, and an important trend at present, to improve the productivity of our present crop varieties, in the frame of a more sustainable agriculture, by using a 'new generation' of chemical fertilisers the so-called slow-release and controlled-release fertilisers. Although they can increase crop yields when used at the same doses than conventional fertilisers (or maintain the same production at lower doses), their effect is not very big. Nevertheless, their use is very positive for the quality of the soil, as these fertilisers cause a lower contamination of soil and water.

'BIOSTIMULANTS'

A plant 'biostimulant' can be defined as any substance or microorganism which, when applied to plants, can enhance nutrition efficiency, crop quality and/or abiotic stress tolerance; these effects are observed at low concentrations of the biostimulant and are not dependent on its possible nutrients content. By extension, plant biostimulants also refer to commercial products containing mixtures of those substances and/or microorganisms. In any case, the use of biostimulants in agriculture is continuously increasing and represents a growing business for agrochemical companies.

Biostimulants can be considered to include the so-called 'biofertilizers' – bacterial or fungal biostimulants increasing the availability of nutrients and their utilisation. Yet, biostimulants should be distinguished from fertilisers, pesticides or biocontrol agents.

The nature of biostimulants is diverse, including 'substances' and microorganisms, single compounds or mixtures of compounds (of known composition... or not), organic compounds and inorganic molecules that are produced in nature or synthetic.

The main groups of biostimulants are the following:

a) Humic substances, including humins, humic acids, fulvic acids and supramolecular complexes of them. They are constituents of the soil organic matter and are extracted from that natural organic matter, composts or mineral deposits.

b) Protein hydrolysates (and additional N-containing compounds), which are generally amino acid and peptide mixtures (purified amino acids and derivatives can also be included in this group), produced by chemical or enzymatic protein hydrolysis of agro-industrial by-products (e.g., animal wastes or crop residues).

c) Seaweed extracts, either crude extracts or polysaccharides purified from them. The use of these extracts as biostimulant should not be confused with the traditional use of fresh seaweeds as organic fertilisers in agriculture.

d) Chitosan (and other biopolymers), derived from chitin, a polymer that can be obtained both from natural sources and industrially.

e) Inorganic compounds, 'beneficial elements' that promote plant growth in some species (but not in all plants), and include, for example, Al, Co, Na, Se or Si.

f) Beneficial fungi, both mycorrhizal fungi such as arbuscle-forming-mycorrhiza (AFM) and non-mycorrhizal fungi

g) Beneficial bacteria, such as *Rhizobium* and related taxa (endosymbiotic bacteria) or plant-growth-promoting rhizobacteria (PGPRs), which are present in the rhizosphere of the plants.

Considering this extreme diversity, it is clear that their physiological functions and mechanisms of action must be also diverse, and are in most cases unknown. A general idea is that biostimulants, somehow, can divert a higher proportion of resources (nutrients, water and light) to growth, increased yield and crop quality, reducing the proportion allotted to activation of stress responses. The elucidation of the specific mechanisms of action of the different groups of biostimulants represents an interesting challenge for basic research in the coming years.

CONCLUSIONS

At the present rates, the increase of agricultural production will not be enough to feed the growing world population. Since drought and soil salinity are the major cause of reduction of crop yields, a problem that will worsen in the coming decades due to the effects of climate change, the most promising strategy to increase crop yields and food production in the near future is to develop stress-tolerant crops, using all available approaches: traditional breeding (with the help of modern biotechnological tools), genetic engineering for the generation of tolerant transgenic crops, or even domestication of wild plant species highly tolerant to salt stress (halophytes) or to water deficit (xerophytes) in their natural habitats.

We can also improve the productivity of our present crop varieties but in the frame of a more sustainable agriculture. This could be achieved by using ‘new generation’ slow-release and controlled-release fertilisers, or by application of low concentrations of the so-called ‘biostimulants’, a disparate group of biological extracts, more or less characterised substances, defined compounds and microorganisms that, regardless of their nutrient content, enhance plant nutrition efficiency, crop quality traits and/or abiotic stress tolerance.

We should be confident that, despite all unfavourable conditions, application of the strategies reviewed above will allow increasing crop yields and food production to the level required to feed the human population in the foreseeable future.

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