Draft Statement

European Plant Science Organisation

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Opportunities Beyond Current Crops

Future demands for novel crops and novel traits

Brussels, 21 May 2013 – Whilst there has been a steady increase in the introduction of new crops/traits for traditional and new uses there is a strong argument that to meet the future challenges of world population growth and climate change a more radical approach is required, with an increased focus on the use of new and novel germplasm resources. To this end an EPSO working group led by Bruce Osborne has produced this draft statement for consultation. Please send all comments and feedback to Bruce Osborne.

THE NEED FOR NEW CROPS

Increasing population growth, agricultural diversification and climate change are arguably placing unprecedented challenges on our crop production systems. By about 2050 the global population will have reached approximately 9 billion, potentially requiring a 50 - 70% increase in food production, as well as an increasing proportion of non-food products. To emphasise the scale of the problem this represents a sustained annual increase in food production of 38% over past historical increases that would need to be sustained for 40 years. As well as the need to enhance crop productivity there is also an increased recognition of the importance of associated nutritional improvements in many of our food crops. These objectives are likely to be constrained by climate-change associated reductions in rainfall, and elevated temperatures and increasingly unpredictable weather patterns, as well as indirect effects, such as increasing soil erosion and salinization and pest infestation. If this were not enough, further pressures are likely to arise due to an increasing shift from resource-intensive to low input systems, partly because of environmental and legislative issues, and the need to reduce the greenhouse gas footprint of agricultural production, but also because of an increasing shortage of available resources, particularly water. We will also have to ensure an appropriate balance between the production of food and non-food products, so that agricultural diversification into non-conventional areas does not impact on food security and human well-being. Significantly increasing the available land area in order to address these issues does not appear to be an option and, overall, crop production for food or non-food products, will have to be more resource-use efficient, where land, as well as more obvious candidates, such as water and nutrients, are all considered as limiting 'resources'.

The key question is how can we achieve enhanced yields from agricultural crops, given the constraints indicated above, with the reduced use of resources? Part of the problem in addressing these issues is that we still have a poor understanding of what determines yield. There is a widely held view that the challenges associated with future crop production cannot be met using conventional or commonly used germplasm and that the development of new crops, or the exploitation of currently underutilized genotypes, will be needed for both food and non-food uses.

MEETING THE NEED

Perceived problems with existing germplasm

The extent to which new crops need to be developed will depend on what relevant genetic variation exists and to what extent this can be utilized to enhance crop productivity and nutritional composition, as well as provide a basis for further development for non-food uses. Another widely held view is that genetic erosion-the loss of variation in crops-has been concomitant with the modernization of crop production systems. Although there may be some support for this, detailed information is still lacking, particularly the functional significance of any reductions in diversity. In part, this problem is also related to what the term ‘genetic erosion’ actually means. Perhaps the most relevant for our purposes is the loss of genes/alleles or varieties, as this could directly impact on the variation required for breeding purposes. Most of the evidence indicates that any reduction in diversity has occurred due to the replacement of land races by modern cultivars, although subsequent modern plant breeding approaches have not led to any changes in diversity. This evidence lends some support to the belief that the more extensive use of land races as an important source of genetic variation is required. As a number of studies have reported an increased resistance to biotic and abiotic factors the increased genetic diversity associated with land races would appear to have a functional basis. Similar arguments could be made for the wild relatives of many crop plants. However, there are a number of problems associated with comparative analyses of land races or wild relatives and their closest crop relatives and there is a need to have a better understanding of the functional significance of any loss in genetic diversity in order that this can be used for improvements in production and nutritional quality. In some respects the threat of genetic erosion is likely to be more significant for crops that are of no apparent use to the breeder, or have been abandoned in favour of more promising species.

Whilst current thinking tends to ignore the variation that exists in commercially-available crops and crop varieties, significant variation may still exist in barley and maize and the significance of this in relation to the future challenges for agricultural production remain to be assessed and exploited. Varieties that were used in the past, particularly under low inputs or sub optimal environmental conditions, may also provide a basis for future exploitation.

On the basis of currently available information, there is clearly a lack of understanding of functional diversity in terms of the major objectives of enhancing crop production for food and non-food uses, particularly under low inputs, whether this involves commercially available or novel germplasm. An often over-looked area is the interaction between beneficial microorganisms and plant growth; with evidence that modern cultivars may be less responsive than older varieties. This may argue for a more holistic approach to achieving the dual objectives of enhancing yield and improving nutritional quality under low inputs where root microbial associations may be particularly important. In turn this may also be important for the production of non-food products given that these are likely to be restricted to marginal agricultural lands.

Whilst the more extensive use of currently-available variation is suggested there are, in particular, non-food production objectives that may require more radical approaches, as well as the identification and utilization of more exotic material. Whilst genetic manipulation may play a part, the assessment of globally underutilized material may also be important, particularly in the short term, as will the continuing search for wild plants of potential agricultural significance. This may be particularly important for non-traditional uses of plants for the production, for instance, of fibre, protein and pharmaceuticals.

What traits?

Given the potential constraints on future crop production, a number of factors need to be considered in the development of new crop varieties; these include increased abiotic/biotic resistance, and improved use of resources, including maximizing productivity per unit land area. A high resource-use efficiency may be particularly important for bioenergy and other non-food uses of plants given their likely restriction to marginal agricultural lands. An important factor that is often overlooked is that nutrient and other resource deficiencies seldom occur in isolation and more work on the impact of combined ‘stresses’ is required. Interactions among a range of environment factors are known to have both negative and positive effects on plants; interactions with carbon dioxide, for instance, may be particularly important for future crop production systems, as increased concentrations of this gas may reduce the impact of water deficits or high temperatures. Unique genes can also be up regulated in response to combined stresses that are not present when these are applied singly. The timing of a particular stress may also be important; for cereals the impact during flowering and grain filling may be particularly important. Interactions between roots and soil micro-organisms can also have both positive and negative effects on plant performance and require inclusion in trait-based assessments.

An over-arching theme, whether the crop is used for food or non-food uses, is the need to enhance productivity per unit land area. An important factor that could indirectly contribute to the enhancement of productivity per unit land area is the greater use of multifunctional crops/cropping systems. To some extent a number of existing crops could be used for this purpose. Maize, for instance, could be used for food, feed or fuel, as could pineapple (Table 1). The further development of second generation biofuel crops should open up more potential opportunities for combined food/biofuel crops.

There has been much interest recently in increasing productivity by improving the photosynthetic performance of crops, particularly the introduction of C_4 photosynthesis into C_3 plants, because of the potentially-higher maximum rates of photosynthesis. However, this is not an option for many potential bioenergy crops as they already possess this photosynthetic pathway or CAM (Table 1). Interestingly, all three major pathways are represented.

Even in C_3 plants there is evidence for significant inefficiencies in the photosynthetic system that may be amenable to genetic improvement. In theory both approaches-introduction of C_4 photosynthesis or modifications in C_3 photosynthesis - could result in significant increases in productivity under the appropriate conditions, but this is a long-term goal.

Crop yield can be related to light utilization by the expression:-

Yield=IR.RUE.HI Equation 1

IR= Intercepted (absorbed) radiation
RUE = Radiation use efficiency
HI = Harvest index

Increases in radiation use efficiency, intercepted (strictly absorbed) light or harvest index could result in yield increases. There is good evidence, however, that the amount of intercepted radiation over the growing season, which is related to the leaf area index and leaf duration/longevity, is often the major driver. Radiation use efficiency is a complex trait, related to the intrinsic efficiency of light energy conversion into stable organic products, leaf architecture/leaf display and, in theory, to feedback regulation of photosynthesis. Based on this information near term targets for genetic manipulation, include modifications in canopy architecture, leaf duration and display, in order to maximise light capture over the growing season. Importantly these traits may be controlled by only a few genes. Whilst the higher potential rates of photosynthesis of C_4 plants do translate into a higher radiation-use efficiency at the canopy scale, under optimal conditions, recent results comparing two C_4 species emphasise the importance of leaf area duration as an important factor in determining differences in vegetative productivity. Maize plants grown in the field had a higher maximum light saturated rate of photosynthesis and a higher quantum (photon) yield at the leaf level than *Miscanthus*, but the latter had the higher biomass production because of longer leaf area duration. Rapid leaf expansion and extended leaf area duration are clearly important factors contributing to differences in biomass production. Whilst these aspects of plant growth are probably not perceived as attractive as those associated with the genetic engineering of photosynthesis they can result in significant gains and may represent a more rational short term approach for achieving higher productivities. This example also indicates the importance of scale-leaf level responses may not directly translate to canopy-scale responses, emphasising the importance of selecting canopy-scale attributes in breeding programmes directed at improving crop performance. Clearly, we should also take account of the potential impact of increasing carbon dioxide concentrations for selecting crops for future agro-ecosystems. Collectively, modifications of canopy-scale traits and the optimisation of resource investment in the components of the photosynthetic apparatus in C_3 plants might double the yield potential of many crops.

It is also well known that photosynthesis can be regulated by feedback control mechanisms, with an impact on RUE (equation 1), operating downstream of the primary carbon dioxide assimilating reactions. At the canopy scale feedback inhibition of photosynthesis could impact on radiation use efficiency. However, little attention has been directed at feedback control as a target for increasing crop performance.

What also needs to be considered is that crop productivity will depend on the balance between gains and losses, although much less consideration has been given to the loss-term, namely plant respiration. It has been known for some time, however, that breeding for reduced respiration in grasses can result in an increase in yield. To what extent respiration is amenable to genetic manipulation is unclear and requires a better understanding of the metabolic and regulatory processes involved.

Increases in crop productivity could also be achieved by the more efficient use of resources, particularly the capture and utilization of N. Indirectly this would increase crop photosynthesis. A number of factors, including improved root architecture and the exploitation of nutrient patches, have been examined. The question, however, is to what extent breeding for improved uptake can compensate for the envisaged reduction in N-inputs, in the absence of any supplementary additions through, for instance, nitrogen fixation?

In the past most of the increase in yield of cereal crops has been attributed to an increase in harvest index (HI; Equation 1), the proportion of above-ground biomass allocated to harvestable product, generally grain. Whilst the maximum HI that can be achieved has been widely debated there is a belief that further gains may be possible, beyond the current value of ~0.50. There has been less consideration, however, of the HI as it applies to root or tuber crops and what might be achieved in the future; increasing investment in below ground non-photosynthetic structures may require different strategies from those directed at increasing biomass allocation towards grain production. As we are likely to be dependent on conventional crops or currently underutilized varieties in the near future for increasing food production, further examination of the limits to increasing HI may be warranted. This emphasises the importance of a better understanding of allocation to harvestable products in general and how this is affected by abiotic and biotic factors.

What crops?

There has been much discussion about what the new or novel crops will be; for the most part this has focussed on bioenergy production, although new crops for fibre, protein, pharmaceuticals, nutriceuticals, and pigments have all been proposed and, in some cases, evaluated and used on a limited industrial/commercial scale. The future prospects for the widespread use of these nascent crops still, however, remains unclear. Breeding for many of the identified uses is still in its infancy. Of the novel candidate crops that could be utilized (see Table 1 for examples) most have had limited use and the majority have been identified primarily for bioenergy production, although there are examples that may be suitable for fibre production and speciality chemicals. Most of the investment in these crops has, however, been outside the EU and the identification of accessions, varieties or species suited to European agro-climatic zones will be important. Interestingly, a number of candidate species are able to be grown with low inputs, suggesting that they already have potential as crops for marginal or degraded lands. Plants with CAM, in particular, appear to hold considerable promise, given their low resource requirements, although they are likely to have only regional significance in the EU due to their climatic requirements.

And what of the future? Exploitation of novel bioenergy crops including algae and cyanobacteria (Table 1), is likely to continue, as is the use of conventional crops, in the short term, for a variety of non-food uses. But what of novel crops for food production? Based on the available information this does not appears to be on the agenda for the near or intermediate future, although investment in this area may be crucial for meeting world food needs. This suggests an expectation that future food supplies, certainly in the near future, will be met through the use of currently available germplasm, whether from commonly grown or underutilized crops, or through their genetic manipulation.

Crop diversification, trait flexibility and combined stress tolerance

Approximately 95% of food production globally is supplied by about 30 crops and the big three-maize, wheat and rice-dominate world food production. However, some 7,500 plants are considered edible and only 0.1% of the world's plant species are grown as crops. This represents a vast untapped resource. There is an argument that the a dependence on such a small gene pool for food production increases the chance of crop failure and that the chances of this are likely to increase as a consequence of climate change and unpredictable weather patterns. In the past variation in the population of individual plants grown compensated in part for the effects of extreme weather events or pest infestations-some individuals survived. The emphasis on uniformity has, however, reduced this variation and potentially resulted in a decrease in the ability of individuals to survive under non-optimal conditions. Arguably, this makes a case for maintaining crop diversity in order to achieve at least some yield in poor years. An alternative is to breed for increased flexibility in the same genotype and improving the capacity for dealing with a wide range of abiotic/biotic factors, by enhancing combined stress tolerance, whilst still providing acceptable yields. Enhancing combined stress tolerance may be particularly important in reducing yield gaps-difference between attainable and achievable yields. That this may be possible is emphasised by recent work on Arabidopsis where combined stress tolerance was enhanced without any yield penalty.

DEVELOPMENT OF NEW CROPPING AND MANAGEMENT SYSTEMS

An improvement in the productivity per unit land area by using multi-functional crops has already been mentioned and management practices that maximise the year-round utilization of agricultural land will achieve a similar objective. In temperate regions this could lead to further investigations into the low temperature tolerance of over-wintering crops. Another strategy could be the offsetting of production to the cooler periods of early spring/autumn, so that for the major part of the growing season crops are not exposed to water shortages/high temperatures. The question really is what is easiest to breed for? Is it a tolerance to high temperatures and low water availability, or a tolerance to low temperatures? The approach used could depend to some extent on the sensitivity of important growth stages to environmental constraints. What is clear is that modified management practices, including the control of pests and diseases, will still make an important contribution to future food and non-food requirements and need to be closely integrated with the development of new crops or the continued use of existing crops.

What may also be feasible is the greater use of mixtures for uses other than for grazing, although this would warrant improved technical innovations for harvesting more than one crop either at the same time or at different times. What may also be significant is the incorporation of N-fixing species, to further improve N availability, without extra inputs. Such a move would require the wider use of N-fixing species in both food and non-food production systems.

CONCLUSIONS

The development of new crops and/or the wider use of underutilized crops are likely to increase in order to meet the challenges facing future agricultural production. To date this has mainly focussed on bioenergy production and there is an argument for greater investment in the utilization of novel crops for enhanced food production. Ensuring food production is not compromised by the development and use of non-food crops, more consideration of an EU-wide land use policy may be required. In the short term enhanced food production will depend on the exploitation of the variation that exists and can be utilized in common crop species and varieties. To this end a better understanding of the genetic diversity of many existing crop varieties and species is required and, in particular, the functional basis of any variation. An over-arching theme for enhancing the performance of both food and non-food crop production systems is an improvement in whole plant photosynthetic productivity and the importance of selection for traits that confer an advantage at the canopy scale. In the short term a focus on canopy attributes may provide a more significant return. Clearly, an increase in resource-use efficiency, where the 'resources' include inputs of water and nutrients, as well as available land area, is particularly important. For non-food production systems traits associated with an ability to achieve maximum yields with low inputs will be essential. Further consideration of the impacts of pests and diseases is also required. In order to accelerate the breeding of novel crops and modified traits new technologies for genotyping and phenotyping will be required, with the capacity to screen thousands of individuals, particularly under field conditions. This question has only partly been resolved using automated phenotypic platforms that are largely restricted in their use to controlled conditions and are costly. Whatever the production system being used there will be an increasing emphasis on crop traits that facilitate the sustainable intensification of productivity. Due recognition of regional differences in soils and climate will also have to be taken into account, when deciding on the most suitable crops and cropping system. Although not currently as attractive as it was in the past the use of N-fixing species and/or the engineering of N-fixation into crop plants via novel symbioses could play an important role in contributing to the nutrient requirements of plants, as could the exploitation of beneficial root-associated microbes. Continuing developments in our understanding and ability to exploit plant-microbe associations may make these more feasible possibilities than they were in the past.

Management practices are likely to still play a significant role in tailoring crops to particular agro-climatic conditions, facilitating the continued use of existing species, as well as enabling the introduction of novel germplasm. Of the possible new production *systems* that might be developed the wide scale use of algae and cyanobacteria appears to offer some promise for both food and non-food uses. Further expansion of organic production systems may require specific breeding programmes. At least in the short term, these two possibilities are only likely to make a small contribution to crop production.

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SELECTED REFERENCES

Amthor, J. (2010). From sunlight to phytomass: on the potential efficiency of converting solar radiation to phyto-energy*. New Phytologist* 188, 939-959.

Atkinson, N. J. And Urwin, P. E. (2012). The interaction of plant biotic and abiotic stresses: from genes to the field. Journal of Experimental Botany 63, 3523-3543.

Boorland, A. M., Griffiths, H., Hartwell, J. & Smith, J. C. (2009). Exploiting the potential of plants with crassulacean acid metabolism for bioenergy production on marginal lands. *Journal of Experimental Botany* 60, 2879-2896.

Dohleman, F. G. & Long, S. P. (2009). More productive than maize in the Midwest-how does Miscanthus do it? *Plant Physiology* 150, 2104-2115.

Evenson, R. E. & Gollin, D. (2003). Assessing the impacts of the Green Revolution, 1960-2000. *Science* 300, 758-762.

FAO (2010). The Second Report on the State of the World's Plant Genetic Resources for Food and Agriculture. FAO, Rome. 399pp.

Karp, A. & Richter, G. M. (2011). Meeting the challenge of food energy security. Journal of Experimental Botany . April 2011 Advanced Access.

King, A. J., He, W., Cuevas, J., Freudenberger, M., Ramiaramanana, D. & Graham, I. (2009). Potential of *Jatropha curcas* as a source of renewable oil and animal feed. *Journal of Experimental Botany* 60, 2897-2905.

Loomis, R. S. & Amthor, J. (1999). Yield potential, plant assimilatory capacity and metabolic efficiencies. *Crop Science* 39, 1584-1596.

Mittler, R. & Blumwald, E. (2010). Genetic engineering for modern agriculture: challenges and perspectives. *Annual Review of Plant Biology* 61, 443-462.

Murchie, E. H., Pinto, M. & Horton, P. (2009). Agriculture and the new challenges for photosynthesis research. *New Phytologist* 181, 532-552.

Ortiz, R. (2011). Agrobiodiversity management for climate change. In Agrobiodiversity Management for Food Security (eds J. M. Lenne & D. Wood), pp. 189-211. CAB International.

Reynolds, M. P., van Ginkel, M. & Ribaut, Jean-Marcel. (2000). Avenues for genetic modification of radiation use efficiency in wheat. Journal of Experimental Botany 51, 459-473.

Reynolds, M., Foulkes, J., Furbank, R., Griffiths, S., King, J., Murchie, E., Parry, M. And Slafer, G. (2012). Achieving yield gains in wheat. Plant, Cell and Environment 35, 1799-1823.

Richards, R. A. (2000). Selectable traits to increase crop photosynthesis and yield of grain crops. Journal of Experimental Botany 51, 447-458.

Sakamato, T & Matsuoka, M. (2004). Generating high-yielding varieties by genetic manipulation of plant architecture. Current Opinion in Biotechnology 15, 144-147.

Tester, M. & Langridge, P. (2010). Breeding technologies to increase crop production in a changing world. Science 327, 818-822.

The Royal Society (2009). Reaping the Benefits: Science and the Sustainable Intensification of Global Agriculture. RS Policy Document 11/09. The Royal Society.72pp.

Van de Vouw, M., Kik, C., van Hintum, T, van Treuren, R. & Visser, B. (2009). Genetic erosion in crops: concept, research and challenges. Plant Genetic Resources: Characterisation and Utilization 8, 1-15.

Xin-Guang Zhu, Long, S. P. & Ort, D. R. (2010). Improving photosynthetic efficiency for greater yield. Annual Review of Plant Biology 61, 235-261.

Zegada-Lizarazu, W., Elberson, W., Cosentino, S. L., Zatta, A., Alexopoulou, E., Monti, A. (2010). Agronomic aspects of future energy crops for Europe. Biofuels, Bioproducts and Biorefining, 4, 2-12.