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Best of the old and the new: a way forward for the food security dilemma?

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THE CHALLENGE of assuring global food security for the world's increasing population — estimated to reach 9 billion by 2050 — has been much discussed. Many solutions have been proffered, but most are from limited perspectives and often represent vested interests of some sort — economic, political, or academic. Many are variations of doing better what has been done before, such as improved agricultural technology and farming practices, minimising waste, making more efficient use of resources (for example, water, land, fertilisers), or negotiating effective trade agreements to manage supply and demand.

My purpose here is to argue that new ideas and disruptive ways of thinking are necessary to conceive adequate solutions to these challenges, and that disruptive 'technologies' will be necessary for their effective implementation. I have been drawn to this conclusion as a result of my current research on improving crop productivity by improving photosynthesis in plants.[1] Photosynthesis converts the freely available resources of energy from sunlight and carbon from atmospheric carbon dioxide (CO_2) into the energy-rich biological sugar compounds ('biomass') and oxygen (O_2) that underpin all life.

I have invented two technologies for increasing the efficiency of the rate-limiting step of photosynthesis, which is the capture ('fixation') of CO_2 into sugars catalysed by the enzyme Rubisco.[2,3] One involves genetically re-engineering Rubiscos of crop plants, while the other involves identifying naturally better Rubiscos among crop-plant wild relatives and breeding this trait into cultivars. Both have many potential applications and both are disruptive, depending on how they might be deployed. Although originally developed as complementary technologies, they could also be used in combination. Having developed these capabilities, I thought more seriously about how I would spend my effort in applying them for the best outcomes.[4] This boils down to 'Which crops?' and 'Why?' Answering these questions provides clear criteria for 'best', and a secure footing to direct food security initiatives.

My approach has been to examine the major assumptions underpinning current global food systems and to assess how relevant they are in today's and tomorrow's world compared with previous eras in which they developed and evolved; in short, to reconceptualise the requirements for global food systems for the future, with a view to identifying best-fit options, especially for crop staples such as grains and legumes.[5] My focus is not merely to address the commonly perceived issue of 'food security', which represents public concerns and responsibilities of governments for food provision, but 'food insecurity' and its crippling impacts on people most at risk of being unable to obtain sufficient, affordable, safe and nutritious food reliably.

I contend that an open-minded analytical approach of laying all the food-security cards on the table, including all the disparate factors usually considered separately — land and resources, climate change, environmental sustainability, food equity, quality, safety and choice, trade, industrial-scale and small-scale farming — actually reduces the complexity of the 'space' of viable or preferred solutions. Thus, some solutions can be seen to produce more robust food systems that are better suited to the needs of the most vulnerable of food-insecure peoples. These solutions are more nutritious, offer more efficient uses of resources, are more environmentally sustainable and better adapted to the growing conditions of the crops, and are more resilient to adverse weather events. Too good to be true? Read on.

What are disruptive thinking and technologies?

Disruptive thinking is a no-brainer — simply, it is a willingness to try to think outside the square. But, willingness to act on it is not so painless! 'Disruptive technology' is a term coined by the business community as an innovation that creates new markets.[6] It might be a 'new' product that outcompetes and displaces existing products, but it could also be a radically new way of doing things that is more efficient or better meets consumers' needs.

I regard my proposal presented here for a radical shift to a new basket of staple food crops chosen as best-fits to the constraining factors listed above as disruptive. Use of such a strong term may help to counter disparaging views that it is a throwback to a more primitive 'natural' agriculture. The usual use of the term is only in a 'forward' sense, but it might be more appropriately defined as a transformational 'technology shift' to a system more appropriate for present conditions of agricultural and human needs, and employing a mix of modern hi-tech, traditional and even ancient[7] innovations.

Crunch time for existing food-crop technology: declining productivity growth

It is widely acknowledged that refinements to 'Green Revolution' paradigm methods are now failing to deliver the continuing improvements in yield necessary to feed the forecast increase in world population, and are increasingly cost-ineffective and environmentally unsustainable.[8,9] There has been a decline in the rate of increase in global productivity of all major food crops (maize, wheat, rice, soybean, and roots and tubers) over the past 50 years; for wheat and rice, from ~3% and 2% from 1960–1990 to less than 1.5% and 1%, respectively, now. Such declines have serious implications, as rice and wheat, together with maize, provide more than 50% of the food calories for the developing world. Previous productivity gains came from plant breeding to improve stress resistance (drought, cold, salinity, pests and diseases), water- and fertiliser-use efficiency, and optimisation of plant architecture. But these improvement strategies have now hit their limits and gains are now in the zone of diminishing returns.

Call for a second Green Revolution? The successes and failures of the first

Among calls for a second Green Revolution (GR), it is worthwhile to ask what we have learnt from the first. The first GR of the mid 20th century has been widely credited with preventing the deaths by starvation of up to a billion people. But it has not been without long-term costs. In addition to breeding in of new traits, such as dwarfing genes, its success derived from changes in farming practices, particularly high use of fertilisers and irrigation. This has led to problems of depletion of soil nutrients and increase in soil salinity due to lowering of the water table. These problems have impacted especially severely on poor farmers in developing countries, often leading to crippling indebtedness. Also, in developed country agriculture, fertility losses and environmental degradation were not included in production costs, and are now a long-term burden on taxpayers and future generations.

The first Green Revolution — vision gone wrong?

The future envisaged by Norman Borlaug, who was awarded the Nobel Peace Prize in 1970, is enlightening. In his Prize speech[10] he said: ‘The green revolution has won a temporary success in man's war against hunger and deprivation; it has given man a breathing space. If fully implemented, the revolution can provide sufficient food for sustenance during the next three decades.' In 2000, in a 30th anniversary lecture[11] he said:

> I now say that the world has the technology — either available or well advanced in the research pipeline — to feed on a sustainable basis a population of 10 billion people. This cannot be done unless farmers across the world have access to current high-yielding crop-production methods as well as new biotechnological breakthroughs that can increase the yields, dependability, and nutritional quality of our basic food crops.

That is, in 1970 and still 30 years later, Borlaug was not presaging different solutions emerging, but arguing for a more comprehensive implementation of GR strategy. His followers have been faithfully carrying this out until it is now crunch time.

Are there now, in 2014, 'new biotechnological breakthroughs' capable of delivering the necessary level of yield increases? Well, no, although the appearance and burgeoning of a new generic technology, CRISPR,[12] in the last year or so may be an inkling of one. Also, improvement of photosynthesis has significant potential, but it has never been a trait targeted in crop breeding because it is difficult to do and the necessary underpinning research has not been done. This position is now changing.

Another view of the first Green Revolution

Kingsbury[13] has offered a different assessment, namely that the GR signified a choice not to start developing better adapted crops, not to focus on improving traditional farming methods, such as mixed cropping for increasing yields, and not to support balanced traditional diets of grains and legumes. Viewed in this light, solving the tough problems has merely been postponed for 50 years or so to a time now when solutions are more urgently required and options more restricted. Borlaug's 'breathing space' has been largely wasted.

What should the second Green Revolution look like?

Our conclusion is that although a step change in plant productivity analogous to the first GR is necessary, its starting point should not be the current status quo. Key impediments to effecting such 'disruptive change' will be economic and geopolitical vested interests of national, international and commercial agriculture and trade, and the scale of investment in physical and other infrastructure supporting them.

In the following I outline a model for what the second GR should look like and why. I also bring together ideas emerging from many perspectives but with converging conclusions that support this model. If well articulated and promoted, together these ideas could generate the necessary momentum to reset the direction of the second GR.

The big questions: supply and demand

To frame this discussion, it is useful to review the obvious but often neglected questions of what do we need to do and why. This reduces to supply and demand of food from crops. On the supply side: What to grow and why? How to grow? Where to grow? When to grow? Who to grow? Why do they grow it?(!) Why don't they grow more? On the demand side: Who eats it and where? What do they eat and why? How do they get it? Is supply adequate, reliable and affordable? Is it nutritious and safe? Who has the power to determine these issues? What real choices do food consumers have? I will focus here on issues most relevant to crops and agriculture, leaving aside the issues of animal protein, which is a major competing use of agricultural resources, and the use of agricultural land for material crops.

What crops do we grow now and why?

Of 50,000 edible plant species, only a few hundred are significant food sources, and a mere 15 crops provide 90% of the world's food energy intake.[14] Just three — the cereals rice, maize and wheat — make up two thirds of this, being staples for more than 4 billion people. This current extreme concentration of the global distribution of food crops is man-made and, moreover, is relatively recent. Historically, crops were domesticated from wild plants growing where people lived, and painstakingly improved by selection for those growing conditions to produce farmers' varieties, with thousands of them differing from village to village. These traditional crops were thus naturally adapted to their growing conditions, including pests, and with large genetic diversity. This robustness allowed a harvestable crop in even adverse seasons, and with more or less natural fertilizers, albeit with low yields.

This system was disrupted by migration of peoples who took their own food crops with them, and later by conquest and colonisation.[15] More recently, disruption escalated with the rise of resource-intensive agriculture, much at industrial scale, based around a few intensively bred crops with low genetic diversity, and largely commercially owned. Increasing productivity, that is, yield per unit of land area, using GR-paradigm methods, has been the dominant driver to meet the increased needs of rapid population growth and urbanisation.

As noted initially, it is generally acknowledged that the 'system is broke'. It is not sustainable on many scores: declining productivity growth, environmental and resource limitations, competition from other uses (materials, biofuels, animal-food production) and thus costs of all types (land, water, fertilizer), climate instability and risk of crop failure, and geopolitical consequences of civil disturbance from increasingly well-informed food-insecure peoples.

What sorts of crops for the future: why and how?

Thinking about the current status led me to question the suitability of the current basket of staple crops and explore which crops would be more sustainable options and the best fit for the future.[16] Integrating perspectives from several directions provided initial insight. First, projected impacts on global and regional food production from global climate change predictions,[17] which has led to the idea of 'climate-ready' crops, have been superseded by recent recognition that the greater risk may be from unreliable or extreme weather events.[18] This suggests that more appropriate criteria for suitability of crops for the future would be those naturally well adapted in the plant evolutionary sense,[19] that is, more reliable and resilient, better able to survive poor seasonal conditions and survive and recover from extreme weather events, such as heat waves, to still produce a harvestable crop. Tilman et al. considered options for expanding global food production with minimal environmental impacts.[20] They concluded that moderate intensification to increase yields of existing croplands of under-yielding nations was preferable to continuing the current trend of greater agricultural intensification in richer nations and greater land clearing in poorer nations.

These views also accord with the main premise of agro-ecology, that 'agriculture should be fundamentally redirected towards modes of production that are more environmentally sustainable and socially just'[21] and the food sovereignty movement,[22] which in essence asserts the rights of peoples and nations to define their own food and agriculture systems rather than having these imposed by corporations and market institutions. It has a large range of incarnations between and among developing and developed countries. For the former, it is usually concerned with protecting the rights of small-scale farmers to grow traditional crops, and antipathy to treating food as a commodity. In the United States it is recognised (without saying so!) by the interesting new term of agricultural 'co-existence'.[23]

But, most critically, which crops should we grow in the future? As I have indicated, my search was to identify the 'best' crop options for implementation of my photosynthesis technologies. I took into account the above insights, but went further and asked the questions, which crops are best prospects to deliver 'more bangs for the bucks' as food, and how and why do they differ from the current main staples?[24] My main criteria were nutritional quality and balance, efficient use of inputs (particularly water, nutrients and land), general hardiness and adaptability to variable growing conditions, and simplicity, flexibility and scalability of farming. But, an additional factor is what type of crop might best be able to exploit increasing atmospheric CO_2. It is known that root and tuber crops, such as potato, are better able to take advantage of CO_2 fertilisation than cereals, as they are not 'sink-limited', that is, biomass produced by photosynthesis (more or less depending on growing conditions) can be efficiently transformed into potatoes (more or fewer), whereas the 'sink' for cereals is limited to that determined at flowering time (for example, number of ears for wheat).

My analysis clearly highlighted deficiencies for rice and maize in nutritional balance (carbohydrate, protein, fats, fibre) and quality (vitamins, minerals, essential amino acids) compared with other major staples such as wheat, potato, sweet potato and legumes, but particularly so for many traditional crops such as quinoa.[25] Rice also has major disadvantages for inputs (very high water and labour needs), farming complexity, and the lowest genetic diversity of any of the crop staples (breeding bottleneck). It also has high vulnerability to predicted climate changes in the main rice-growing areas, which are already experiencing temperatures close to those critically high for development of the rice plant.[26] Thus, I asked 'Why rice — not fit-for-purpose?', unsurprisingly not a popular question as national, international and commercial agriculture is fixated on solving rice's problems, despite the fact that rice-eaters rapidly shift to other foods as rising incomes allow a more varied diet.

The benefit of increasing photosynthetic capacity of a crop plant is that it widens its margins to cope with both extreme short-term weather events and poor seasonal growing conditions and still produce a harvestable crop. It is the key trait to produce such benefits, as it produces the plant's energy that can be used to repair damage from heat, pollutants, disease, insect or other damage. But even in adverse conditions there is enough energy (biomass) left over for transformation into grain or tubers. That is, it doesn't just give 'more bangs for the buck', but more reliable 'bangs for the buck'. My conclusions, and their congruency with the insights of others, discussed above, from other criteria, provide clear guidance for where efforts at improving photosynthetic capacity are best deployed, that is, which crops.

New concepts consistent with these proposals

Several new concepts relevant to food security and models for global food systems have emerged, some already touched on above. The drift of these ideas is substantially different from the 'monolithic' economic thinking of governments, large corporations and many international structures such as trade agreements. Many are human-focused and appear to show that people from both the developed and developing world are taking a greater interest in where their food comes from and how it is grown. They go beyond issues of food security, and reflect the concerns and aspirations of citizens and consumers who are increasingly well-informed by access to global communication and knowledge. The importance, emphasis or interpretation of these concepts varies greatly from country to country, region to region, and developing to developed countries, and they are intriguingly interrelated. A short list is: food sovereignty,[27] right to food, food equity and food as a commons,[28,29] consumers' rights, de-linking food and water as commodities,[28,30] virtual water and water footprint,[31] agroecology, environmental sustainability and preservation of biodiversity,[32,33] peak resources,[34] and agricultural co-existence.[35]

Disruptive thinking and technologies: reassessment and review

As presented here, a shift to traditional, more nutritious crops, more sustainable farming practices, more local production and consumption, and greater control for producers and consumers over what they grow and eat does not imply simply a return to peasant agriculture; this was not fun. Rather, we are in the happy position in the 21st century of being able to meet all the above aspirations and use affordable, advanced technology; for example, use of remote sensing and weather prediction, landscape measurement of nutrients, soil carbon, water table, and quadcopters to optimise farm management, timing of sowing and harvesting, labour management, and advanced crop breeding and biotechnology. Could we see a resurgence of the increasingly savvy and prosperous yeoman farmer, including in developing countries?

This vision requires developing more flexible and 'nimble' agricultural systems that are more responsive to changing conditions. Modern biotechnology — such as plant transformation, plant phenomics, genomics and metabolomics, high-throughput analyses of nutritional content and bioavailability — makes this possible without the long lead times needed historically to develop, trial and introduce new crops. A major advantage of such a disruptive change, with a fresh start applying modern methods to an expanded portfolio of crops, is that it would allow concurrent development of crops with resistance to biotic (for example, plant diseases) and abiotic (for example, salinity, heat) stresses, and increased photosynthetic yield potential and nutritional composition starting from a rich gene pool. Designer crops fit-for-purpose assembled from natural and/or GM gene components! Boosting photosynthetic capacity may provide the necessary breathing space to get the rest of this agricultural redirection right. Thus, the cost of 'cutting losses' is not as great as might be thought.

A stiff dose of intellectual honesty in consideration of the following hard questions

Whose needs are we trying to satisfy? Who are the real stakeholders? Hungry or food-insecure people, now and in 2050? Is it the well-fed rich who demand more food variety, especially more meat and other resource-intensive foods? Is it current vested interests, not only in commercial agriculture, but also food exporters and trade and other infrastructure, and international agriculture institutes promoting 'their crops' when evidence points to better options, such as quinoa?

Entrenched ideas, fatalism, inertia and vested interests conspire to prevent humans from timely action. History shows such failure to confront the inevitable eventually leads to massive disruption and pain as the system is finally forced to redirect itself. History also shows that bold new ideas and concepts — and usually champions to promote them — provide the catalyst that drives the necessary change. But it can take a long time for such ideas to take hold. Will humanity actually have the time to redirect itself this time?

Endnotes

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