

Biofortification: improving the nutritional quality of staple crops

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Deficiencies in vitamins and minerals in our diets create major public health problems, mental as well as physical, especially in developing countries. Conventional responses (diet diversification, supplementation, fortification of manufactured foods) have had limited impact.

This chapter analyses a different approach now emerging – biofortification. Rather than adding something new to diets, it seeks to improve the nutrient content of the staple crops most people eat most of the time.

The three forms of biofortification are described and exemplified – enhanced fertilisers, conventional breeding, and nutritional genetic modification.

The chapter then considers major issues that will influence the future development of biofortification: (a) new target levels for nutrient content of crops; (b) the time required for the full implementation of biofortification programmes; (c) the pros and cons of regulating biofortification, including the perverse effect of stimulating the production and smuggling of, and trade in, illegal crop varieties; (d) the relevance of biofortification to small, poor farmers; (e) the different environmental effects of nutritional and agronomic GM crops; (f) the practicalities of distributing biofortified seeds to remote subsistence farmers in developing countries; (g) the recent convergence of poverty reduction and biofortification as development strategies.

The chapter concludes by considering how we will know if biofortification works, and when.

For a third of the planet's population, excess is not a problem but an aspiration. The destitute dream of dissipation. For those who live on less than \$2 a day, however, reality is hunger and malnutrition.

In the round numbers appropriate to global generalizations, at least two billion people suffer from deficiencies of minerals and vitamins (the micronutrients), especially iron, iodine, vitamin A and zinc. The majority suffer several shortages simultaneously.

The poor in the poorest countries suffer most, in nutrition as in everything else. They are the jetsam of the mega-cities and the isolated in rural areas. They cannot pop down to a shop to buy healthy foods or nutritional supplements. Often, there are no shops. Where they exist, the poor cannot afford to buy in them. They lack physical or economic access, or both.

There has been progress against iodine-deficiency diseases in recent years, mainly though the spread of iodized salt – salt being one of the few basics that even the poor and the remote actually buy.

For the other micronutrients, public health interventions have mainly involved supplementation programmes, the fortification of processed foods and diet diversification, all with or without nutrition education programmes attached.

All have encountered practical problems – recurrent costs to the state, the international agency or the consumer; erratic coverage because of the logistics of distribution; or the unacceptability to the intended beneficiaries of what is on offer. With the most widespread problem, iron-deficiency anemia, ‘all interventions to date have been universally unsuccessful’ (Zlotkin et al, 2005). Changing people’s diets is difficult – as the continuing failures in developed societies, in much easier conditions, attest.

Whatever the cause, the consequence is that malnutrition continues at very high levels. Micronutrient deficiencies not only affect physical health, but mental health as well – the cognitive stunting of children, poor educational performance, lower work productivity. In developing countries, malnutrition is an economic as well as a health issue.

Now a different strategy has emerged. Instead of trying to add something healthy to habitual diets, the logic is to start from the staple crops that people eat already, and then improve their nutritional quality. Access is built-in from the beginning. The strategy is ‘biofortification’ – fortification in the field rather than in the factory. The promise it holds out is nutritional improvement without dietary change.

Forms of biofortification

There are three forms of biofortification: enhanced fertilisers, improved plant varieties through conventional breeding, and the same goal through nutritional genetic modification. All three are in use or development.

Enhanced fertilisers

The role of fertilisers is to provide nutrients that plants need in order to grow, principally nitrogen, phosphorus and potassium. Enhanced fertilisers provide additional nutrients needed by the people who eat the plants. Successful examples include enrichment with iodine in China, selenium in Finland and zinc in Thailand. This approach has an important advantage – it works quickly.

But as a long-term strategy for improving public health, enhanced fertilisers have serious limitations. They are expensive and have to be applied regularly. So their use involves recurrent costs. They are also heavy and bulky, making distribution difficult where roads are bad or non-existent.

The two other forms of biofortification raise issues of their own, but they do overcome these problems. The system planned for both is an initial, subsidised distribution, a one-off cost. Farmers could then harvest and use seed for future years, as they do with existing varieties now.

The potential of biofortified crops, therefore, is to provide a continuing supply of micronutrients to large numbers of people, without recurrent costs or logistical

Table 1: ‘HarvestPlus’ biofortified crops.

Crop	Nutrient	Countries	Release
Bean	Iron (Zinc)	Congo, Rwanda	2010
Cassava	Provitamin A	Congo, Nigeria	2011-12
Maize	Provitamin A	Zambia	2011-12
Rice	Zinc (Iron)	India, Bangladesh	2012-13
Wheat	Zinc (Iron)	Pakistan, India	2012-13
Sweet potato	Provitamin A	Uganda, Mozambique	2007
Pearl Millet	Iron (Zinc)	India	2011

Table 2: Stages of biofortification.

Discovery	1. Identify target populations 2. Set nutrient target levels 3. Screen germplasm and gene
Development	4. Breed biofortified crops 5. Test performance of new crop varieties 6. Measure nutrient retention in crops/food 7. Evaluate nutrient absorption and impact
Dissemination	8. Develop strategies to disseminate seeds 9. Promote marketing & consumption of biofortified food
Outcomes	10. Improve nutritional status of target populations

problems. They should be much more cost-effective than existing strategies (Meenakashi et al, 2010; Stein et al, 2006). Combining economic savings with the technical developments, biofortification opens a path towards ‘nutrition security’ (Shetty, 2009).

Conventional breeding

Large differences exist among the many varieties of the same plant, in nutritional characteristics as well as many other traits. Accelerating since the 1960s, seed banks have been developed to collect and catalogue these variations. The International Maize and Wheat Improvement Centre in Mexico (CIMMYT) is a leading example. The new Svalbard Global Seed Vault, inside the Arctic Circle, will become the most comprehensive.

From such collections, it is possible to develop, through conventional breeding, new variants of staple crops with better nutrient profiles, based on lines that have proven suitable for the growing conditions in specific areas.

Breeding to improve food crops goes on all over the world, mainly focussed on improving yields rather than nutrient profiles. The most significant, systematic and symbolic programme of biofortification through conventional breeding is

HarvestPlus. It focuses on breeding increased levels of three nutrients (iron, zinc and pro-vitamin A) in seven staple crops (beans, cassava, maize, rice, wheat, sweet potato and pearl millet).

The initial test projects, in developing countries of Africa and Asia, are summarized in Table 1.

The HarvestPlus programme is funded principally by grants from foundations, governments and international agencies. Started in 2003, within the Consultative Group on International Agricultural Research (CGIAR), it works with specialist institutes in that network and with outside, public sector and academic researchers.

In HarvestPlus's conception, biofortification is a ten-step process, with assessment at each stage, see Table 2.

If successful, the crops tested in the initial biofortification projects will be disseminated to numerous 'spillover countries' with similar growing conditions, including areas of Latin America. The first results from the first project, sweet potato biofortified with pro-vitamin A, are expected in 2010.

Nutritional genetic modification

All discussions of genetically-modified (GM) crops should begin with the distinction between the two basic types of GM. In the industry, they are known as Phase I and Phase II, or Input and Output GM. In plain English, they are Agronomic and Nutritional GM.

Agronomic modifications aim to help the plant grow better. All GM crops in production so far are of this type, in China as in the US. The most common GM food crops are herbicide-resistant soybeans and pest-resistant maize. But current research, with global warming and water scarcity in prospect, also focusses on drought and salinity-resistant varieties of many crops.

Nutritional modifications aim to improve the nutrient profiles of crops. They add nutrients totally absent from all varieties of a plant, or present only in small amounts. In such cases, improving nutrient profiles through conventional breeding is not possible.

De facto, biofortification has evolved a two-stage strategy: breeding if possible, modifying if necessary (Beyer, 2009).

Many types of nutritional GM have been explored, in both developed and developing countries. They include essential fats in oilseeds, varied starches and protein in potatoes, iron in rice, minerals in horticultural crops, glucosinolates in brassicas, flavonoids in vegetables, and a range of 'golden' plants (rice, maize, cassava, banana, potato, cauliflower, sweet potato, mustard), so named because the inserted gene for beta-carotene, which converts into vitamin A, provides a yellow-orange colour.

A complementary part of nutritional GM involves reducing 'anti-nutrients' in plants, notably allergens, glycosides and the phytate that inhibits the absorption of nutrients. Lowering phytate increases the 'bioavailability' of nutrients, that is, it allows consumers to absorb more from a plant – even without increasing the levels in that plant. Both approaches are often applied in the same plant.

The main effort to date, however, as with conventional breeding, has focused on the providing the micronutrients missing from the staple crops of the developing world. The most prominent example is 'Golden Rice'. It will become the first nutritional GM crop in widespread cultivation, when it goes into production in the Philippines in 2011-12 (Beyer, 2009).

The distinction between agronomic and nutritional GM is not just an academic issue, but also a practical, indeed political one. It is critical because of controversy that has surrounded GM crops in Europe and, to a lesser extent, elsewhere.

The two types of GM are different – in their technical characteristics, in their research and development paths, in the economic model that underlies their distribution, in their environmental effects. Most importantly, they are different because nutritional GM provides a perceptible consumer benefit that agronomic GM so far has not. And that benefit is uniquely valued – the improvement of human health.

So, nutritional GM may also have political consequences. If it succeeds in delivering demonstrable public health gains to the poor and malnourished of the world, it could influence the debate about genetic modification in general.

Meanwhile, from its technical beginnings in adding small amounts of single nutrients, nutritional GM has now moved into a new phase – adding several nutrients to the same plant. In trade jargon, this is 'stacking', in more scientific terminology, 'multigene transfer'.

This approach is most visible in the Gates Foundation's Grand Challenge 9 Programme, to 'Create a full range of optimal, bioavailable nutrients in a single plant species'. Four projects all focus on a similar package of nutrients: increasing the levels or bioavailability of iron and zinc, vitamins A and E, plus protein. They work on bananas for Uganda, sorghum and cassava for Africa generally, and rice for Asia.

The rice 'challenge' is an expansion of the original 'Golden Rice project. It will also incorporate, into future variants, an extension of the 'stacking' logic – including agronomic properties, tolerance to submergence or resistance to blight and disease, as well as multiple nutritional improvements. Indeed, combining agronomic and nutritional modifications, appropriate to specific growing regions as well as food cultures, may be essential to the success of nutritional GM (Sands et al, 2009), because the yields of biofortified variants will be critical to their acceptance by farmers.

Another major centre for multigene transfers, aiming to produce 'nutritionally complete crops', is the Christou group at the University of Lleida in Spain. Its 'multivitamin corn' has achieved high levels of beta-carotene (ultimately, vitamin A), ascorbate (vitamin C) and folate (vitamin B9) in a single plant (Naqvi et al, 2009a). Field trials have begun.

Combining several nutrients in the same carrier food is also a trend in other strategies against micronutrient deficiencies. Following the success of iodized salt, production has recently begun in India of double-fortified salt, with added iron. Trials are underway with treble-fortified salt, including vitamin A as well.

Micronutrient powders, popularly known under their original name of Sprinkles, are a form of 'home fortification' that also provide several nutrients at once. In sachets for a single serving, they are sprinkled on top of normal foods. Beginning with just micro-

encapsulated iron, they have now developed numerous varieties, with as many as 15 vitamins and minerals, appropriate for the nutritional problems of specific areas.

In theory, nutritional GM could expand this principle. In the view of the Christou group, 'the simultaneous introduction of tens of transgenes into plants now seems a distinct possibility'. However, possible interactions among genes may limit the process. Much testing will be required. (Naqvi et al, 2009b).

In developed countries, work on nutritional GM by private sector firms began early. However, after the European Union's opposition to GM technology became obvious in the late 1990s, investment and research fell off (Graff et al, 2009). Relatively few examples are now in product development pipelines.

The most significant current work concerns another important global deficiency, but one that is not so widely recognized – of omega-3 fatty acids, particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). Monsanto is introducing a modified soybean that is an intermediate solution. But BASF's modified rapeseed/canola contains substantial amounts of EPA and DHA themselves. It is now seeking regulatory approval (Napier and Graham, 2010).

All these initiatives on biofortification are promising – but as yet, nothing more than that. Neither conventional breeding nor nutritional modification has progressed enough to make any impact on public health so far. And they may never do so. Ahead lie issues that need to be resolved if biofortification is to fulfil its promise. These are not just the complex technical problems of genetics or nutrition, but also the social and practical problems of access.

Will politicians permit the initiatives? Can the seeds for the new crops be distributed to remote areas? If so, will farmers grow them? Or simplest of all, will people eat them? In many parts of the developing world, sweet potato, maize and cassava are as white as polished rice. How will consumers react if they suddenly become orange? Will they be more accepting than Western consumers have been of purple cauliflower?

Issues in biofortification

Target nutrient levels

How much do the amounts of nutrients need to be increased? The simple answer is they need to be high enough so that people get sufficient from the amount of the staple crop that they would normally eat in a day. The complex answer is: it depends. It depends, in part, on public health goals. The aim may be just to eliminate overt deficiencies, or to provide average requirements, or to ensure that no one goes short, or to achieve some 'optimal' level of nutritional well-being.

The target level rises with the level of ambition. The grand challenge, to provide a 'full range of optimal, bioavailable nutrients' in a single plant, sets the bar high.

All targets must also take account of nutrient losses that occur through local forms of storage and cooking. Research on retention in sweet potato demonstrated only modest losses (Boy and Miloff, 2009), but will need to be repeated with all biofortified crops.

Increased nutrients in the plants are also effectively 'lost' because they are not bioavailable, not absorbed by consumers. Early research suggests that added beta-

carotene in plants converts well into vitamin A in consumers (Tang et al, 2009). But bioavailability will vary between plants and nutrients, so adjustments to targets levels will be necessary.

The target also depends on how important the crop is in the local diet. In Bangladesh, for example, on average 84% of dietary energy comes from rice, so the total absence of vitamin A in rice is a serious issue, and biofortification levels must be correspondingly high.

Conversely, they may be reduced if other local foods provide some of the same nutrient. For example, HarvestPlus's zinc target for rice in Bangladesh is to meet 40% of average requirements. The practical consequence is that there are considerable variations in both targets and achieved levels under different biofortification initiatives. For example, HarvestPlus has set a 'preliminary' target of 77 micrograms (μg) of iron per gram (g) for pearl millet in India, but 94 $\mu\text{g/g}$ for beans in Rwanda. The levels of beta-carotene in the latest version of Golden Rice are up to 31 $\mu\text{g/g}$, and approximately 60 $\mu\text{g/g}$ in multivitamin maize.

But in all cases, these are just the levels at the time of writing. Biofortification, whether by conventional breeding or nutritional modification, is a 'stepwise' process of incrementally increasing nutrient levels (Wu et al, 2005). And this, in turn, allows the raising of initial targets to meet higher health objectives, as technology and skill improve. The process could go on a long time.

Transformation time

Biofortification is no quick fix. Both the principal forms involve long development times, especially because biofortification is not just a technical matter of designing new seeds, but a multi-stage social process of transforming production, consumption and ultimately health.

To take an extreme example, conventionally-bred Quality Protein Maize, for which two developers at CIMMYT won the World Food Prize in 2000, has been under more or less continuous development since 1963, and has still achieved only limited distribution.

Against that background, it is often argued that genetic modification speeds the process of breeding. But such advantages are only relative. Partly because of the political and regulatory controversies over GM technology in general, the first nutritional GM crop, Golden Rice, has been under development for 18 years and is only shortly to enter production.

A balance may also be struck between the level of fortification and the length of development. If target levels are modest and some varieties of the crop already contain the relevant nutrient, then conventional breeding may be quicker, or at least quick enough. That is part of the logic behind HarvestPlus's approach. But even HarvestPlus is a 15-year programme.

Regulation

The legal framework governing conventionally-bred plants is relatively simple. But genetically-modified crops are thought to raise safety issues that require regulation of their development and use. Obtaining regulatory approval has become an additional lengthy process.

The current demand is for 'biosafety' laws, modelled on the Cartagena Protocol on Biosafety. The logic is that such a potent new technology should only be adopted after careful consideration of possible unintended consequences – a 'precautionary principle' or, less conservatively, a 'precautionary approach'. In this view, the absence of evidence for harm to human health from GM crops so far does not obviate the need for continued vigilance.

Much debate, theoretical and practical, surrounds the Cartagena approach (Falck-Zepeda et al, 2009). Is it more appropriate for multinational seed companies than poor developing countries? Does it incorporate an absolutist, unrealisable concept of zero risk (Nuffield, 2003)? Does it consider the risks of doing nothing? Can it also incorporate benefits, balancing them against risks?

More than 100 nations, most of them poor developing countries, currently have no biosafety laws. Progress in creating them has been slow. One practical issue is that the cost of establishing a full regulatory system is beyond the means of many governments – and hence works against crops specifically intended for the developing world, like nutritional GM.

Even if biosafety laws are passed, it is uncertain whether developing countries have the human and technical capacity to implement them. Could they assess candidate crops, conduct trials, monitor whatever is approved?

Burkina Faso, one of only eight African countries with a formal regulatory framework, has established a school to train regulators. This is just one of many capacity-building initiatives – creating laboratories and containment facilities, training technicians and crop breeders, educating extension workers and agro-dealers, establishing databases. There is still much to do.

But biosafety laws are not just about safety. Behind them lie other agendas, pressed by the principal interest groups. For multinational seed companies, they are a way of protecting intellectual property and maintaining high prices. For local companies, they provide a form of protectionism, legitimated as 'food sovereignty', defending against techno-colonialism. For those opposed to GM altogether, demanding safety standards can be tools for obstruction and delay.

For better or for worse, strong biosafety laws can also be counter-productive. The more costly they become, in terms of time, money and effort, the more they stimulate evasion.

Extra-legal GM

To circumvent the constraints and costs of regulation, the smuggling and imitation of established GM seeds have become widespread.

In China, which has a complex biosafety system, the two principal forms of approved GM cotton, from the Chinese Academy of Agricultural Sciences and from Monsanto, accounted for only 10% of the country's GM cotton acreage. The other 90% was planted with derivatives of these two originals, many initially produced in government crop-breeding institutes (Huang et al, 2007). As with designer watches and blockbuster videos, the knock-offs outnumber the official products.

Similar developments in India (GM cotton) and Brazil (GM soybeans) have been described chronologically, in detail, by Herring (2007). In both countries, seeds were first smuggled, then saved, cross-bred, repackaged, given numerous new brand

names, sold, exchanged and planted. In Gujarat, new varieties were produced by farmers themselves, sold unpackaged, unbranded, as 'loose seeds', in farmer-to-farmer transactions (Roy et al, 2007).

Such activity has been vividly described as 'Robin Hood genetics', or 'agrarian anarcho-capitalism', or 'bio-hacking' as a counter-cultural cottage industry, producing 'stealth seeds'. In both countries, the governments were unable to stop the spread of unapproved varieties. Eventually they capitulated, legalizing what they could not control.

More than a lack of enforcement capacity was involved, a lack of will to enforce as well. In both countries, there were splits within and between both central and regional governments. Some politicians forcefully defended the derivative seeds as an effective, pro-poor form of technology diffusion, bringing advanced agriculture to farmers who could not otherwise afford it.

The entrepreneurial adoption of GM seeds by farmers also managed to antagonize equally both pro-GM multinational seed companies and anti-GM non-governmental organisations. These farmers were pragmatic and proactive pursuers of their own interest, even if that meant acquiring GM seeds that others would deny them.

The three examples reveal the political economy of GM technology and biosafety regulation in all its fractured complexity.

Big vs small

These accounts also contrast with the common perception in the West of GM technology as the preserve of big seed multinationals and big commercial farmers. In fact, most of the 14-million users of GM seeds are actually small farmers. Some 90% of them are in China and India (James, 2010). They are growing the same GM cotton (or extra-legal derivatives) as the big agri-businesses of North America. GM technology is 'scale-neutral'.

That is relevant for biofortification, which is concerned first and foremost with small farmers in developing countries. Big companies have not been involved in the conventional breeding approach. Nor much in nutritional GM either, except for a handful of members in larger public research consortia. The reason is obvious – there is not much money to be made from subsistence farmers.

As a result, biofortification has been funded largely by international foundations and governments. Golden Rice began with grants from Switzerland and the Rockefeller Foundation, which continues as its principal donor to this day. The Gates Foundation is a major funder for HarvestPlus, the Grand Challenges, CGIAR and a number of smaller initiatives like the African Biosafety Network of Expertise.

Environmental effects

The introduction of GM technology understandably raised questions about its potential environmental effects. Two of the major issues illustrate the differences between agronomic and nutritional GM.

One concern is the possible transfer of inserted genes to non-target species, the 'gene flow' problem. With herbicide-resistant soybeans, this raised the possibility of 'superweeds', other plants that could not be eradicated by conventional agro-chemicals.

Nutritional GM, in contrast, does not confer significant ecological advantages on a plant. Containing more pro-vitamin A does not help it grow or endure better. However, possible future combinations of agronomic with nutritional traits, foreshadowed above, might blur the clear dichotomy.

Initially, there was concern that new GM crops would become so dominant that biodiversity would be reduced. That is not how nutritional GM works. With plants and agriculture, one size definitely does not fit all. The genes that improve nutrient profiles have to be inserted into existing plants suited to local conditions. For example, part of the Golden Rice programme is to include its package of nutrients in the 11 varieties of rice most commonly grown in Asia. Biofortification reinforces diversity.

Distribution

After the labyrinthine high-tech development of biofortified seeds, getting them to farmers might seem the easy bit. Both major programmes of biofortification promise to turn their seeds over, free of charge, to the governments of developing countries, for distribution through national systems. Thereafter, mechanisms will vary.

In Africa the infrastructure of seed distribution is 'primitive'. In the DR Congo, for example, distances are vast, roads scant, transport often possible only by water, with millions of small farms to be reached, some in areas disrupted by a long and brutal civil war. But biofortification is important. Two-thirds of the population suffer some form of malnutrition.

The response, in the past three years, has been a succession of schemes – public, private, academic – to improve seed availability to remote farmers: the African Seed Investment Fund, the Program for Africa's Seed Systems, the Seeds Development Programme, the Seed Enterprise Management Institute, the Ghana Agro-dealer Development.

Such programmes are necessary because more than just wholesaling is required. Many small farmers are not only remote, but cannot read or write and speak a variety of dialects. Seed merchants thus also function as supplements to often under-funded agricultural extension services.

The focus is on developing African-owned, small and medium-sized enterprises. They are not so glamorous as international research institutes, but also a necessary link in the chain of biofortification.

Poverty

Equality is not the ethos of the age. In terms of calories and nutrients, as well as money, gross disparities prevail. Some starve, others are morbidly obese. Some exist on less than \$1 a day, others accumulate more than \$1 a second.

In reaction, one of the enduring strategies to improve diets focuses not on food, but on poverty. If the poor had more money, they could buy more and better food. Recent events have turned this radical hope into mainstream policy.

The global food crisis of 2008 drove commodity prices to historic highs, provoking food riots in some 40 countries. By common consent, such crises are likely to recur. In addition, climate change – rising temperatures, water shortages, desertification – will put pressure on food production at a time when global population is rising, further pushing up the prices of basics.

This combination of short and long-term factors has suddenly given agriculture heightened priority after decades of neglect. Politicians promise more investment, better research, technology transfers, increased incentives to food producers. This revival comes at a time when development policies emphasize small farmers, raising their productivity, output and incomes. It also coincides with the effort on biofortification. Which is useful, because when people obtain more money, they do not always spend it on the foods that nutritionists and environmentalists approve. Biofortification itself has always had a strong economic logic. Reducing malnutrition in childhood will lessen the physical and mental stunting that reduces productivity in adulthood (Anderson and Jackson, 2004). Together they create, in theory, a virtuous circle – if the poor have more money they can buy a better diet, and eating a better diet enables them to earn more money.

This phase may not last. Political priorities may change. The rich North may not deliver its pledges to the poor South...again. Nonetheless, at the beginning of the 21st century, development and nutrition policies coalesce.

Will biofortification work?

Biofortification is a long, multi-stage process. It is being evaluated every step of the way – precaution in practice. But at the end of the day, it will be judged, by people and by politicians, on whether it improves human health.

In this regard, biofortification has advantages over many nutrition interventions. With heart disease, for example, researchers must wait decades to see if diet changes made any difference. So they measure ‘process variables’ or ‘intermediate end points’ instead, not final outcomes.

But the health consequences of malnutrition show themselves quickly – anemia in women, blindness in children, early death. *If* biofortified staple crops make a difference, *then* these improvements will also appear quickly, within five to ten years. Happily, evidence for improvement, if it occurs, is easily and inexpensively available. In some degree, however incompletely or imperfectly, national governments and international agencies already do much basic epidemiology, gathering health statistics. That is why we know, roughly, the scale of global malnutrition.

Both the principal programmes of biofortification, conventional breeding and nutritional modification, are about to go into production on a scale sufficient to test their effectiveness. So, we may have a reasonable idea whether biofortification works by 2020.

References and further reading

For earlier sets of readings and overviews of the field, see

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For recent collections on the field, see

Science and Development Network, January 2010, Series of articles on strategies for coping with malnutrition on available at: <http://www.scidev.net/en/editorials/urgent-action-needed-to-tackle-malnutrition.html>

Information Systems for Biotechnology, January 2010, Special issue: biofortification of plants through genetic engineering, <http://www.isb.vt.edu/news/2010/Jan10.pdf>

Hyperlinks

Biofortification programmes

HarvestPlus, www.harvestplus.org Separate entries on nutrients, crops and projects under this general heading

Grand Challenge 9, Create a full range of optimal, bioavailable nutrients in a single staple plant species, available at:

<http://www.grandchallenges.org/ImproveNutrition/Challenges/NutrientRichPlants/Pages/default.aspx>

Separate entries on all four projects under this heading. Three also have their own websites:

Golden Rice Project, <http://www.goldenrice.org>

BioCassava Plus <http://www.biocassavaplus.org>

Biosorghum <http://biosorghum.org>

Seed banks

Svalbard Global Seed Vault, http://en.wikipedia.org/wiki/Svalbard_Global_Seed_Vault

CIMMYT (International Maize and Wheat Improvement Center), <http://www.cimmyt.org/>

Double-fortified salt

Micronutrient Initiative: <http://www.micronutrient.org/english/View.asp?x=584>

Tamil Nadu Salt Corporation: <http://www.tnsalt.com>

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