BEST PRACTICE PAPER: NEW ADVICE FROM CC08

BIOFORTIFICATION

J.V. Meenakshi

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Best Practice Paper

Cost-Effectiveness of Biofortification

J. V. Meenakshi

This paper is based and builds on earlier work by HarvestPlus research collaborators (see Meenakshi et al, 2007). I am grateful to a reviewer for helpful comments on an earlier draft. The usual disclaimer applies.
Cover image credit: The International Rice Research Institute, 2002.

PREFACE

For two years before Copenhagen Consensus 2008, a team of experts wrote papers identifying the best ways to solve the world's biggest problems.

Those papers showed that we have the knowledge to do tremendous amounts of good in each of these areas.

That research was utilized by a panel of top economists, including Nobel laureates, who were commissioned by the Copenhagen Consensus Center to identify the most effective investments.

The prioritized list produced by Copenhagen Consensus 2008 provides governments, donors and philanthropists with a guide to the areas where relatively small amounts of money can prove extremely powerful.

The research that provided the building blocks to this process – and a full description of the outcome – form the book, 'Global Issues, Global Solutions, Volume Two', published by Cambridge University Press in 2009. This is an excellent overview of global problems and the most promising solutions.

Given the level of interest in Copenhagen Consensus 2008, the Copenhagen Consensus Center decided to commission a specific set of papers that deal with the spending options given highest priority by the expert panel.

The goal of these Best Practice Papers is to provide clear and focused empirical recommendations on the costs and benefits of implementing the solutions, and advice on how to do so.

The problems dealt with by Copenhagen Consensus 2008 are vast. The practical approaches identified here prove incredibly powerful reading. The Copenhagen Consensus Center hopes that they shall prove an invaluable resource, and further advance the goal of promoting the most sound investments to help humanity.

Bjorn Lomborg
Copenhagen, 2009

INTRODUCTION

By any standard, the magnitude of micronutrient undernutrition is immense. Nearly 2 billion people suffer from iron deficiency, a quarter of the world's population is at risk of inadequate zinc intakes, and the magnitudes for vitamin A deficiency are similarly high. Unlike the case with insufficient energy intakes, micronutrient malnutrition has often no obvious manifestations except in extreme cases, and is for this reason often termed "hidden hunger". It is only appropriate, then, that of the top ten solutions ranked by the Copenhagen Consensus, five are addressed to reducing malnutrition. It is also an acknowledgement that a problem so widespread needs more than just one set of solutions or interventions to have appreciable impact (Horton, Alderman and Rivera, 2008a).

Biofortification is one such intervention, ranked fifth by the Consensus (Copenhagen Consensus, Results, 2008), along with supplementation (ranked #1), fortification (ranked #2), deworming and school nutrition programs (ranked #6) and community-based nutrition promotion (ranked #9).

The premise of biofortification is that a diverse diet rich in micronutrients is out of reach of many of the world's poor. Because foods that are high in micronutrients such as vegetables, fruits, dairy, and meats are expensive, resource-poor people rely primarily on a few starchy staples that are rich in energy, but not in micronutrients. Dietary diversity to achieve micronutrient intake adequacy is a luxury that the poor can often not afford. By enhancing the micronutrient content of these energy-rich staples, micronutrient intakes in general, and among the poor in particular, can be increased, thereby leading to a reduction in the prevalence of micronutrient undernutrition. The objective of biofortification is to develop micronutrient dense staple crops to achieve provitamins A, iron and zinc concentrations that can have a measurable impact on nutritional status.

For the biofortification strategy to be successful and cost-effective, three questions must be answered: first, plant breeders must succeed in finding lines with high micronutrient content that can be bred into local varieties. Second, the nutritional efficacy of a biofortified crop must be established, and third, both farmers and consumers must accept the new variety and make it an important part of what they produce and consume, so that it becomes a cost-effective intervention.

Thus far the answer to the first question appears to be positive, in that it is possible to increase the content of some micronutrients (but not others) to the minimum target levels that have been set by nutritionists as necessary to measure biological impact. For example, a high-zinc rice is being developed for release in Bangladesh by 2012; however, achieving the iron target in rice may take longer. It has also not been possible to increase the provitamins A levels of rice using conventional breeding techniques; golden rice is a transgenic crop. Similarly, orange sweetpotatoes rich in provitamins A have been released in Uganda, but it appears not feasible to appreciably increase the mineral content of this staple using conventional breeding techniques. The evidence on nutritional efficacy is also building—the case has been made for orange sweetpotatoes (van Jaarsveld et al, 2005) and similar research is under way for other crops. An effectiveness study in Mozambique has demonstrated that there was an appreciable increase in serum retinol levels among young children as a consequence of consuming orange sweetpotato even in a community setting (Low et al, 2007).

This paper attempts to answer the third question on the cost effectiveness of biofortification, by reviewing the evidence on its costs and potential health benefits. It is ex ante in nature, since with few exceptions, biofortified crops are yet to be released. The paper presents a typology for analyzing the cost-effectiveness of the intervention and examines the sensitivity of the results to alternative assumptions on coverage and impact.

Like fortification, biofortification is a food-based approach. Its niche is that it targets rural areas, where a large part of crop production is consumed either on-farm or locally, and reliance on purchased food products that are processed centrally is small. For example, much of the maize flour in rural Zambia is milled in hammermills with relatively small capacities. While fortification at this level has been shown to be technically feasible, it is also relatively expensive, because of the monitoring costs involved (Omar Dary, personal communication). Similarly, in rural Bangladesh, rice is usually milled in small-capacity mobile and traditional mills. As Fiedler (2007) notes: "if a large proportion of the food item is produced or processed by small scale producers, the food is likely to be less attractive as a fortification vehicle. In such instances, compliance with the fortification standards or regulations is likely to be more variable, and more difficult and expensive to ensure." It is perhaps for this reason that the Micronutrient Initiative expects that the coverage of fortified foods in rural areas may not exceed one-third. Because biofortification works at the level of each individual crop plant, it can serve to reach rural populations not easily served by other interventions.

But how cost effective is this intervention? This review examines the key drivers of the costs of biofortification, and how they influence cost effectiveness. The paper is organized as follows. Section 2 first presents some summary evidence on costs per DALY saved from biofortification, and presents a simple framework that is useful for understanding how costs and cost-effectiveness depend on specific contexts. It then presents a more detailed analysis for four country-crop-nutrient case scenarios, each representing a typology that categorizes the ease with which a biofortified staple food could take root in the target country. Three of these cases are for crops that are conventionally-bred; the fourth examines the evidence for transgenic biofortified crops. In Section 3, the paper considers issues related for consumer acceptance of a new crop, when the biofortification translates into a visible change in its appearance. This is the case with crops that are high in provitamins A which are orange in color, and thus distinct from the white varieties that are conventionally consumed. Section 4 presents conclusions.

1 ANALYZING THE COST-EFFECTIVENESS OF BIOFORTIFICATION[1]

In principle, biofortification is an extremely attractive intervention, since a one-time investment in biofortified crop varieties yields a benefit stream year after year. There are virtually no recurring costs, except those involved in maintenance breeding. These of course vary, and are

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[1] The unit of currency used in this paper is the US dollar.

estimated at about $100,000 per year in Bangladesh and $2 million per year in India. In comparison, both fortification and supplementation involve recurring costs: incremental costs of fortification are estimated at $20 million a year in Bangladesh alone (Fiedler, 2008).

The well-accepted metric—Disability-Adjusted Life Years (DALYs)—forms the basis for determining impact and cost effectiveness. Before the publication of the *Lancet* (Black et al., 2008) series, a modification of the DALYs framework, adapted specifically to an analysis of micronutrient malnutrition, was developed by HarvestPlus, and is the basis of the figures presented in this paper. In calculating cost-effectiveness, the focus is only on the health benefits that accrue as a consequence of biofortification, and not on the agronomic (yield) benefits that may also be embodied in a biofortified staple.

While the details of the methodology are set out in (Stein et al, 2005), the key assumptions underlying the assessment of the impact and cost-effectiveness of biofortification in reducing the DALY burden involve the following (Meenakshi et al, 2007 has details):

- The incremental quantity of micronutrients in the grain—as determined by plant breeders, and based on the minimum target levels set by nutritionists as necessary for a measurable health impact. This is determined by examining the natural variation in the germplasm and is taken as fixed in the simulations that follow.
- The quantity of the staple food crop consumed by target populations—the greater the consumption the greater the impact. An example may be illustrative: with a 300 gram per day consumption—not unreasonable for an adult woman in many developing countries—the addition of 4 parts per million (ppm) of iron to the staple would translate into an increased intake of 1.2 mg per day of the nutrient. A lower level of consumption, say 100 grams, would translate into increased iron intakes of only 0.4 mg per day. Unfortunately, reliable data on the quantity of foods consumed disaggregated by gender and age group is rarely available; yet this information is critical to analyses of potential impact (Fiedler et al, 2008). For this reason, the simulations below vary the level of consumption and examine how cost-effectiveness results change as a consequence.
- Nutrient losses in food preparation—this is a particular concern with provitamins A which may degrade quickly when exposed to sunlight or to certain forms of processing, such as fermentation. Boiling for example, translates into retention levels of about 80% (Bengtsson et al, 2008), but retention levels for other processing methods can be much lower (Nascimento et al, 2007). The simulations for provitamins A examine the sensitivity of results to changes in processing losses.
- Coverage rates—the greater the share of a country's food supply that is biofortified, the higher the magnitude of impact. But this depends both on farmers' and consumers' acceptance of biofortified staples and the availability of infrastructure for dissemination. Clearly, this is a key parameter for impact, and the cost simulations take these into account.
- Costs: The cost-effectiveness figures here include costs of research and development of the new variety since these are significant up-front costs. These are apportioned to the potential set of target countries using production shares. While these costs include breeding for multiple nutrients, the cost-effectiveness figures attribute total costs to

each individual nutrient, since there is no obvious way to apportion costs between zinc and iron, for example. Both nutrients tend to be correlated in many crops (Pfeiffer and McClafferty, 2007), so that breeding for high zinc often translates into higher iron levels in the grain as well. Also included are country-specific costs of adaptive breeding, maintenance breeding, and dissemination and nutrition education campaigns.

- Health benefits and costs are discounted at 3 percent per year, as is usual in the health economics literature. The paper also examines the sensitivity of the results to the use of a higher discount rate of 6%.
- Although the paper focuses on DALYs—which are a direct measure of health benefits—to facilitate comparisons with other interventions through the calculation of a benefit-cost ratio, DALYs are monetized at $1000 per DALY saved. While this figure is somewhat arbitrarily chosen, this figure has been suggested by Horton et al (2008b) as being appropriate for low income countries in South Asia and Sub-Saharan Africa, which are the primary target regions for micronutrient interventions.

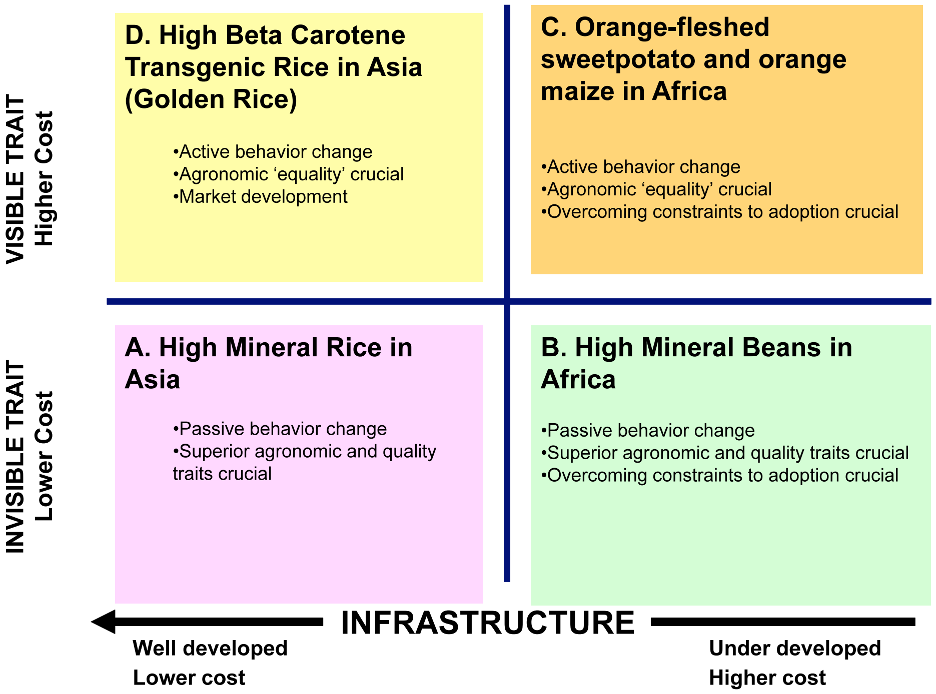
These assumptions are the basis of calculations summarized in Table 1. Because the analysis is ex ante in nature, pessimistic and optimistic scenarios are used to capture the sensitivity of results to changes in assumptions. All the best-case assumptions are used for the optimistic scenario, while all the worst-case assumptions constitute the pessimistic scenario. It is clear that nearly all the interventions are extremely cost-effective even in the pessimistic scenario, with most costs per DALY saved lower than the $200 cut-off often used to categorize interventions as "highly" cost effective. Not unexpectedly, impact and cost-effectiveness estimates vary not only by crop and nutrient, but also across countries.

Table 1. Impact and cost-effectiveness of biofortification (range of estimates)

Micronutrient	**Percent reduction in DALY burden**		**Cost per DALY saved**	
Crop	**Pessimistic**	**Optimistic**	**Pessimistic**	**Optimistic**
Zinc:				
Rice	13-20	33-56	6-55	1-12
Wheat	5-9	33-48	11-18	1-2
Iron:				
Rice	4-8	11-21	17-234	3-55
Beans	3-9	16-36	134-439	20-65
Vitamin A:				
Cassava	3-5	19-32	124-1000	8-127
Maize	1-8	17-32	113-289	11-18

Source: Meenakshi, J.V., Nancy Johnson, Victor Manyong, Hugo De Groote, Joy Javelosa, David Yanggen, Firdousi Naher, James Garcia, Carolina Gonzales and Erika Meng, "How cost-effective is biofortification in combating micronutrient malnutrition? An ex ante assessment" 2007: HarvestPlus Working Paper 2.

Figure 1. A typology for analyzing cost-effectiveness of biofortification



Source: HarvestPlus, http://www.harvestplus.org/endusers.html, "Reaching End Users" Retrieved December 9, 2008.

What factors help explain this variation in cost-effectiveness? Figure 1 presents a simple framework for analyzing how costs may vary. Clearly, the potential coverage of biofortified varieties—both in terms of the share of the crop area devoted to biofortified varieties, as well as the percentage of consumers who would consume biofortified staple foods—is key. This in turn depends on whether there is a well-developed dissemination infrastructure for the new crops (on the horizontal axis) and whether consumer acceptance is likely to pose a hurdle (on the vertical axis).

Quadrant A depicts a situation where there is good dissemination infrastructure and where the trait is invisible; biofortification is likely to be highly cost effective in this scenario. In contrast, costs are likely to be higher where dissemination infrastructure is not as well developed, and where the trait is invisible (Quadrant B) and higher still in situations where the infrastructure is relatively poor, and the biofortified trait is visible (Quadrant C).

Mineral-dense cereal crops in South Asia best exemplify Quadrant A. Cereal area in South Asia tends to dominated by a few mega varieties. For example in Bangladesh, the top five varieties account for over half the rice area in the Aman season and nearly two-thirds of the rice cropped area in the Boro season. Maximal adoption rates for the successful varieties were achieved in as little as five years from introduction (Jaim and Hossain, 2007). By ensuring that the high-zinc lines are back-crossed into the popular mega varieties, and by also introducing the high-zinc trait into new generation of varieties that are to be released, high coverage rates may be feasible within a relatively short period of time. Crops in Sub-Saharan Africa exemplify

Quadrants B and C, since most African countries have relatively poor extension and seed systems infrastructure. For this reason, the percentage of area of major staples in Sub-Saharan Africa that is devoted to modern varieties does not approach the levels found in South Asia (Evenson and Gollin, 2003). Farmer-to-farmer exchange is common, and where the variety is hybrid, subsidies may often be necessary. For example, Zambia was able to achieve 75% coverage of modern varieties as long as seed was subsidized, this figure plummeted to about one-third coverage when the subsidies were removed (Mungoma, personal communication). Mineral dense crops in this continent therefore are an example of Quadrant B.

Provitamins A is a visible trait that imparts a distinct orange color to the grain or root. Because of this, there may be low acceptance by consumers, even if high coverage rates are feasible through agronomic superiority. The costs necessary to achieve substantial impact for countries-crops-nutrients in these quadrants (C and D) are likely to be much higher than in Quadrant B. Costs for a transgenic crop with a visible trait may also be high, even if such biofortified crops are deployed in countries with well developed infrastructure (Quadrant D).

The cost-effectiveness of biofortification may be examined using this framework, using a typical example from each of the quadrants. Also highlighted is how results may vary depending on the assumptions used.

Table 2. Impact and cost-effectiveness of zinc-dense rice in Bangladesh: sensitivity to assumptions on coverage and consumption levels (quadrant A)

	Percent reduction in DALY burden of zinc deficiency	**Cost per DALY saved (USD)**
Coverage varies from 10 to 60%		
10	5	26
20	10	13
30	14	9
40	18	7
50	22	6
60	25	5
70	29	4
Consumption levels among young children varies from 50 to 150 grams per capita		
50	10	13
100	18	7
125	20	6
150	25	5

Source: Author's calculations, based on Meenakshi et al (2007).

1.1 Well-developed dissemination infrastructure, invisible trait: the case of zinc-dense rice in Bangladesh (Quadrant A)

Table 2 presents changes in impact and cost-effectiveness results based on alternative assumptions on coverage and the quantity of staple food consumed. The maintained assumptions are:

- An increment of 10 ppm of zinc is added to polished rice (as consumed) a target that plant breeders expect to achieve by 2012. Because the nutrient content is measured in polished rice, processing losses are not relevant, since there is only an insignificant loss of mineral during the boiling of rice.
- Consumption of rice averages approximately 150 grams every day among young children, and biofortified rice varieties will account for 60% of the total rice supply in the country over a 20-year period.
- Research and development costs average $300,000 per year; adaptive breeding costs are approximately $100,000 per year and last for five years; and maintenance breeding and dissemination costs (and minimal social marketing costs) add up $100,000 per year and are incurred for the last 20 of the 30 years timeframe considered in the analysis.

These assumptions translate into reduction in the DALY burden of zinc in Bangladesh of nearly a quarter, at a cost of $5 per DALY saved. Even with a relatively low coverage of 10%, it is clear that high-zinc rice in Bangladesh will be highly cost-effective even though the impact on the DALY burden of zinc undernutrition is a relatively modest 5%; with coverage rates closer to 70%, nearly 30% of the DALY burden would be saved, at a cost of $4 per DALY saved. The table also presents evidence on the sensitivity of the results to changes in the levels of consumption of rice, keeping coverage fixed at 60%. In areas where only 50 grams of rice are eaten every day by children in this age group (one-third of the 150 grams assumed above), a 10% reduction in the burden of zinc deficiency could be achieved. It would nevertheless continue to be a highly cost-effective intervention at a little over $13 per DALY saved.

The use of a higher discount rate does little to alter the conclusion: at a 6% rate of discount, under the maintained assumptions outlined in the bullets above, costs would increase to $11.30 per DALY saved (Table 5). These translate into extremely high benefit-cost ratios: if DALYs saved are valued at $1000 each, this would translate into a benefit cost ratio of 198 when costs and benefits are discounted at 3%. At a 6% discount rate, the benefit cost ratio would drop to 89.

To what extent might similar results obtain for other crops/countries in this quadrant? Results are comparable for Eastern India, not surprising given similar prevalence of micronutrient malnutrition, and diets that are also based on rice. For other rice-based economies in South East Asia as well, benefit-cost ratios are likely to be high (see for example Javelosa, 2006).

1.2 Under-developed infrastructure, invisible trait: the case of iron-dense beans in Rwanda (Quadrant B)

Rwanda is representative of this typology, with high levels of anemia (56% among children), and with per capita consumption of beans being among the highest in the continent. There is no formal seed system per se, and informal seed markets and farmer-to-farmer exchange predominate as the source of seed. Iron-dense beans are expected to be released in late 2010. Table 3 demonstrates the expected cost effectiveness of biofortification in Rwanda, and its sensitivity to changes in coverage and consumption. The underlying assumptions are:

- An increment of 40 ppm is added to beans, a target that plant breeders have already achieved
- Consumption among children is about 30 grams per capita per day, and coverage reaches 20% over 20 years; there are no processing losses
- Research and development costs average $200,000 per year; a figure arrived at by apportioning global research and development costs to potential target countries using production shares; adaptive breeding costs are about $100,000 per year and last for five years, while maintenance breeding and dissemination costs are $50,000 per year and are incurred for the last 20 of the 30 years timeframe considered in the analysis.

Table 3. Impact and cost-effectiveness of iron-dense beans in Rwanda: sensitivity to assumptions on coverage and consumption levels (quadrant B)

	Percent reduction in DALY burden of iron deficiency	**Cost per DALY saved (USD)**
Coverage varies from 10 to 60%		
10	2	25
20	4	13
30	6	9
40	8	7
50	10	5
60	12	4
70	14	4
Consumption levels among young children varies from 30 to 70 grams per capita		
30	4	13
50	7	8
70	10	5

Source: Author's calculations, based on Meenakshi et al (2007)

These assumptions translate into a four percent reduction in DALYs saved annually, at a cost of about $13 per DALY saved, which is extremely cost effective, even with a low coverage rate of 20%. If coverage were to expand to 50%, Rwanda could see a 10% reduction in the burden of iron deficiency, at a cost of $5 per DALY saved. The assumption on the level of consumption of beans, relative to the other staples being considered in this paper, is relatively conservative. The table also examines the impact of using a higher consumption level for beans—which is a co-staple in the average Rwandan diet. Doubling the consumption translates into a more than doubling of the reduction in the DALY burden of iron deficiency in Rwanda, and as a consequence, more than halving the cost per DALY saved. No matter the assumption used, the intervention appears highly cost-effective.

Once again, this conclusion is relatively robust to the choice of discount rate used: increasing the discount rate for 3 to 6% translates into an increase in cost per DALY saved from $13 to $18 (Table 5) under the maintained assumptions of a maximum coverage of 20%, and consumption levels among children of about 30 grams. Evaluated at $1000 per DALY saved, these translate into extremely high benefit-cost ratios of 78 (at 3%) and 56 (at 6%).

Similar cost-effectiveness figures are likely to obtain in neighboring regions in Burundi, and the Kivu provinces of the Democratic Republic of Congo, all of which have relatively high consumption of beans. In countries such as Kenya and Tanzania as well, biofortified beans are likely to be cost effective.

1.3 Underdeveloped infrastructure, visible trait: the case of provitamins A maize in Kenya (Quadrant C)

Table 4 considers a similar set of calculations, presented this time for maize, and taking into account changes in assumptions regarding coverage, consumption levels, and processing losses. Because the coverage of modern varieties in most African countries is not as high as the levels that have been demonstrated in South Asia, the cost calculations assume a maximum coverage of 50%, lower than the 60% considered in Bangladesh. Note that seed systems in Kenya are, relatively speaking, better than in much of Sub-Saharan Africa. Once again, the maintained assumptions are:

- An increment of 15 ppm is added to maize, a target that plant breeders expect to achieve by 2012.
- Processing losses average 50% percent, consumption among children is 150 grams per capita per day, and coverage reaches 50% over 20 years
- Research and development costs average $300,000 per year; this figure is arrived at by apportioning global research and development costs to target countries according to production shares; adaptive breeding costs approximately $200,000 per year and last for five years; maintenance breeding and dissemination costs are $100,000 per year and are incurred for the last 20 of the 30 years timeframe considered in the analysis. Relative to the costs in Bangladesh, the costs in Kenya are higher both in per capita and per acre terms

Under these assumptions, Kenya could see a 30% reduction in its burden of Vitamin A deficiency at a cost of under $30 per DALY saved. This translates into 36,000 DALYs saved annually. With coverage rates at 70%, a 40% reduction could be achieved, with a cost of $23 per DALY saved. Should consumer acceptance pose an obstacle, however, and coverage rates don't exceed 10% even after 10 years, a 7% reduction in the DALY burden could be achieved, at a cost of $125 per DALY saved. Turning to the sensitivity of these figures to changes in consumption levels, if consumption levels among young children were only one-third those assumed here, the costs per DALY saved would be closer to $80, since this would translate into only a 11 percent reduction in the burden of Vitamin A deficiency. Finally, the table also sets out how cost-effectiveness varies depending on processing losses. If processing methods involve prolonged exposure to sunlight, it is likely that much of the additional betacarotene in the maize will be lost. In this case, losses of up to 70% are possible. The costs in this situation would be more than double that of the scenario considered, at $65 per DALY saved. If losses were as low as 30%, provitamins A maize would cost $23 per DALY saved.

Table 4. Impact and cost-effectiveness of provitamin A maize in Kenya: sensitivity to assumptions on coverage, consumption levels, and retention (quadrant C)

	Percent reduction in DALY burden of vitamin A deficiency	**Cost per DALY saved (USD)**
Coverage varies from 10 to 60%		
10	7	125
20	14	65
30	20	45
40	25	35
50	30	29
60	35	25
70	39	23
Consumption levels among young children varies from 50 to 150 grams per capita		
50	11	77
100	22	41
150	30	29
Retention of provitamin A varies from 30 to 70%		
30	20	23
50	30	29
70	39	40

Source: Author's calculations, based on Meenakshi et al (2007).

Table 5 shows how the cost-effectiveness results change with a higher discount rate: the intervention continues to be highly cost-effective at a 6% rate of discount with a cost per DALY saved of $41, and a benefit cost ratio of 24.

High provitamins A maize is similarly likely to be cost-effective in other eastern and southern African countries, which have predominantly maize-based diets. For countries with lower levels of maize consumption, such as those found in western Africa, target increments necessary to achieve biological impact will need to be commensurately greater.

The comparison of Bangladesh and Kenya highlights the relatively higher costs—and a greater sensitivity of the cost-effectiveness results to underlying assumptions—in Kenya than is the case in Bangladesh. Two main factors drive this: first, the population base—and hence the burden of micronutrient deficiency is much higher in Bangladesh than in Kenya. 440,000 DALYs are lost to zinc deficiency in Bangladesh each year, while DALYs lost to vitamin A deficiency in Kenya are 120,000. Second, costs per person (and per acre of crop) are likely to be much higher in Kenya than in Bangladesh. This is on account of the higher costs of dissemination in Africa in general, and the fact that a greater multiplicity of varieties—both

Table 5. Sensitivity of results to magnitude of discount rate used; under maintained assumptions

	Zinc-dense rice in Bangladesh	Iron-dense beans in Rwanda	Provitamin-A maize in Kenya
Cost/ DALY saved (USD)			
Discount rate of 3%	5	13	30
Discount rate of 6%	11	18	41
Benefit-Cost Ratio (Benefits valued at $1000 per DALY saved)			
Discount rate of 3%	198	78	34
Discount rate of 6%	89	56	24

Source: Author's calculations, based on Meenakshi et al (2007).

open pollinated and hybrid—are cultivated in Kenya as compared to Bangladesh. Also, because of the visible trait, a more elaborate and perhaps prolonged nutrition information campaign is likely to be necessary in Kenya as compared to the level of intensity (and cost) of a nutrition campaign that will be necessary with the invisible zinc trait in rice in Bangladesh.

1.4 Well-developed dissemination infrastructure, visible trait and transgenic: the case of golden rice in Asia (Quadrant D)

While the paper thus far has focused exclusively on conventionally-bred crops, a few words on transgenic crops are in order, as the potential for a biofortified maize, for example, that has genes that impart drought tolerance, or a provitamins A rice that has submergence tolerance genes can be immense. Biofortification could then ride on a much-prized agronomic trait to high levels of coverage. Transgenic crops also offer the potential for significantly increasing the amount of the micronutrient that is available, and offer the possibility that more than one micronutrient can be incorporated into the staple food. But to the extent that transgenic crops also face obstacles in terms of public concerns as to their safety, achieving wide coverage may not be feasible, placing such crops in the upper left quadrant of the schematic depicted in Figure 1.

Under the grand challenges in health programs, research is currently under way to examine the feasibility of introducing micro and macronutrients into cassava, sorghum, banana and rice. With the exception of golden rice, there are relatively few studies that examine the cost-effectiveness of transgenic biofortified crops. Stein et al's (2008) results are particularly instructive, since they are based on the same methodology that underlies the other cost estimates presented in this paper, this enables direct comparisons. Stein et al's results suggest that golden rice is highly cost effective in India, at a little under $20 per DALY saved, even under a low impact scenario. The low impact scenario assumes a coverage rate of between 15 to 20 percent, and includes regulatory costs of over $2 million, total research and development costs of $8.5 million, and social marketing costs of approximately $15 million. They find that this result is robust to changes in assumption about coverage rates and costs, in each case being lower than the cost per DALY saved of the next cheapest intervention. Earlier work by Dawe et al (2002) and Zimmerman and Qaim (2004) in the context of other Asian countries has qualitatively similar results. Since regulatory mechanisms for the introduction of transgenic crops are still to be in put in place in many developing countries, the potential reach of a transgenic biofortified crop in the next five to ten years appears limited to a few countries, including the Philippines, India, and South Africa.

2 HOW WILL CONSUMERS REACT TO A VISIBLY-DIFFERENT STAPLE FOOD CROP?

The coverage rates that biofortified crops reach depend not only on producer acceptance, but also on acceptance by consumers who may resist a staple food that is visibly different in appearance and perhaps taste. What are the grounds for optimism about consumer acceptance of an orange colored maize, or a golden rice? In a fascinating account of the introduction of maize varieties into the African continent, and its spread to displace the traditionally cultivated sorghum and millets, James McCann (2005) devotes an entire chapter titled "How Africa's Maize turned White". He notes that:

> "Despite the recent evidence that African consumers are now rather firmly entrenched in their preference for white maize, earlier Africans' aesthetic sensibilities regarding food and symbol caused consumers to select colored maize, ranging from crimson to blue, to colorful mosaics of red, blue, yellow and orange, either on different ears, or all mixed on a single ear. Historically, many local consumers in Africa expressed strong preferences for red or blue or orange or yellow kernels, or for variegated mixes of all of the above. In the early 1960s, the presence colored maize on African markets began to recede, as national trends favoring white maize overtook older local traditions." (McCann, 2005, pp. 113-114).

The switch to white maize, then, appears to have started less than fifty years ago, dictated largely by commercial compulsions and trade. Of course, the distribution of yellow maize bred primarily for feed as food aid has imparted a negative connotation, both on account of poor sensory characteristics such as aroma and taste, and the association with times of hardship.

In more recent years, economists have focused attention on whether a biofortified maize will be accepted in Africa. De Groote and Kimenju (2008) comparing white and yellow maizes (but not an orange biofortified maize), note that on average, consumers needed a substantial 37% discount to switch from white to yellow maize. While there was a premium for commercially-fortified maize, it was only about 6 to 7% in magnitude. However, the magnitude of the discount to induce a switch was much lower for poorer consumers. A study conducted in Zimbabwe about consumers' perceptions about yellow maize suggested that nutrition education was the single most important factor in influencing acceptance of yellow maize, and that poorer consumers were more likely to accept yellow maize than richer consumers (Muzhingi et al, 2008).

If orange maize is believed equivalent to yellow maize, these studies indicate that the task of expanding coverage under a pro-Vitamins A maize is indeed an uphill one. However, a study conducted by Stevens and Winter-Nelson (2008) in urban Maputo, Mozambique, focused on a deep orange biofortified maize, and compared it to an isogenic white maize. Their results suggest that "existing preferences for white maize may not preclude acceptance of orange biofortified maize." Also, a more recent survey in Zambia that included both sensory evaluation and willingness to pay components, and compared white, yellow and orange varieties, concluded that consumers did not confuse orange for yellow varieties, and found orange maize to be as acceptable or more acceptable than white maize; while yellow maize had, on average, the lowest acceptability scores. In fact, orange maize appeared to sell at a premium relative to white maize (HarvestPlus, ongoing research). This is also corroborated by a similar study of orange sweetpotatoes in Uganda (Chowdhury et al, 2008). Clearly more research is needed to address whether in fact the orangeness of the biofortified varieties will prove a selling point, or whether the negative perceptions about yellow maize will carry over to these varieties.

What if an orange colored biofortified crop is also transgenic?

If, in addition to being an unfamiliar color, the crop is also genetically modified (GM), this may pose an additional hurdle to overcome for achieving wide coverage. There have also been some studies on the consumer acceptance of a biofortified transgenic crop, all of them using methods of elicitation that rely on hypothetical (but incentive-compatible) scenarios, since a transgenic biofortified crop has not yet been released. The results suggest that in contrast to Europe where the opposition to transgenic foods appears entrenched, in the developing countries that are the target of biofortification, consumer attitudes are not so negative, especially when given information about the nutritive value of the foods. A few examples are illustrative: a comprehensive survey of farmers, urban consumers and rural consumers was undertaken in the Philippines to assess the acceptability of a 3-in-1 GM rice, with enhanced provitamins A, resistance to tungro, and resistance to bacterial leaf blight. More than two-thirds of the respondents indicated that they would accept a biofortified (golden) GM rice, an equal number indicated that they would plant it, or buy and consume it. A quarter would plant/consume it under certain conditions, that related largely to concerns about the perceived adverse effects of GM foods on health. Asked if they would be willing to pay higher price for a GM rice that met 50% of the recommended dietary allowance for vitamin A, about 30% indicated that they would not do so, while about half the consumers indicate their willingness to pay between 1 and 10 percent more. These magnitudes were comparable to those for the agronomic trait of pest and insect resistance (Gonzales et al, 2008a).

Results suggesting that a GM biofortified crop may find acceptance also appear from Brazil, from the PhD research of Carolina Gonzales, who focused on a biofortified cassava in the poorer North-East region of Brazil with a relatively high prevalence of Vitamin A deficiency. Her results (Gonzales et al, 2008b) suggest that consumers might be willing to pay a high premium for a biofortified cassava that could help alleviate VAD, implying the potential for improvements in health far outweigh any negative perceptions that Brazilian consumers have about GM foods.

Finally, a study conducted by the Indian Institute of Management also finds support for the lack of widespread consumer opposition golden rice in India (Deodhar et al, 2007).

Studies about public perceptions do not, of course, translate into a smooth sailing regulatory process. India has seen a large number of "public interest litigations" seeking to block all transgenic foods being argued in the Supreme Court. The approval of any one crop may enable the quicker release of biofortified GM foods that appear to be waiting on the shelf (a high iron rice backcrossed into a popular mega variety in Bangladesh is a good example).

3 DISCUSSION AND CONCLUSIONS

The paper has reviewed the cost-effectiveness of biofortification for four case studies that represent a range of scenarios that are likely to be realized as biofortified crops are deployed. The ability of biofortification to make a substantial impact on the magnitude of micronutrient malnutrition varies considerably, depending on coverage, which in turn depends on whether there is well-developed infrastructure to support seed dissemination, and whether the trait is visible or not.

As with any ex ante analysis, examining the sensitivity of the results to changes in assumptions used to derive cost-effectiveness figures and benefit-cost ratios is necessary. Tables 2 to 4 highlight the context-specificity of the impact of biofortification and of its cost-effectiveness; mineral-dense crops in South Asia enjoy a considerable cost advantage over provitamins A crops in Sub-Saharan Africa, even though in terms of percentage reduction in DALYs the case for a provitamins A maize is stronger than for the other crop-nutrients. In most cases, biofortification continues to be highly cost-effective even with relatively low coverage levels and corresponding impact on the magnitude of malnutrition. These conclusions remain largely robust to the choice of a higher discount rate of 6%, even though as expected, with a higher discount rate, costs are higher (and benefit-cost ratios lower) as compared to the case where a 3% discount rate is used. The implications of using different discount rates are nicely illustrated and summarized in the Challenge paper by Horton, Alderman and Rivera (2008a).

At first glance, these benefit-cost ratios may seem too high to be credible, particularly in Quadrant A for countries such as Bangladesh. Note however that benefit-cost ratios of 100:1 have been reported for vitamin A supplements in Ethiopia, attributed to the high mortality rates there (Horton et al, 2008b). However, there are several reasons for these apparently 'high' benefit-cost ratios. First, South Asian countries have large populations, implying that for a given prevalence rate more DALYs are lost—and can be saved through biofortification—in South Asian countries than in most African countries. Second, the invisible trait makes for easier acceptance by farmers and consumers. Third, the predominance of a few mega varieties in cropping patterns means that large numbers can be reached with the same investment. Fourth, relatively modest coverage rates that have been assumed of 60% in South Asia, 20% is Sub-Saharan Africa. As coverage expands, the benefit-cost ratio is likely to fall. But in general, benefit-cost ratios for biofortification are intrinsically high, because the large research and development costs are incurred up-front and there are relatively small recurring costs, especially in Quadrants A and B. Therefore a large one-time investment yields a continuous stream of benefits, unlike the case, say, with supplementation, where recurring costs of distribution must be incurred year after year.

By and large, the assumptions on the costs are conservative: for example as mentioned earlier, where an increase in the content of more than one micronutrient is effective, the costs are not apportioned by micronutrient (and are therefore double those that would have obtained had they been apportioned). To the extent however that the visible trait proves to be a barrier to acceptance, leading to lower coverage rates than those used here, actual costs may be higher.

As noted in the introductory section, the paper is silent on valuing the non-health benefits that may accrue from the adoption of a biofortified crop. This is only appropriate given that it is the *marginal* costs and benefits from biofortification that are the focus of this paper. But to the extent that the biofortified trait is to be piggy-backed on agronomically superior lines, the benefits to the farmer from a biofortified variety are clearly higher. While quantification of the agronomic benefits of varieties into which the biofortified trait will be mainstreamed is beyond the scope of the paper, Evenson and Gollin (2003) provide a comprehensive review of the benefits and costs of modern variety development in developing countries. For example, Johnson et al (2003)estimate that the rate of return to genetic improvement in cassava was in the range of 9 to 22% with about one-fifth of the cassava area in Africa being planted to material developed in the international agricultural research system . Estimates for Sub-Saharan Africa tend to be lower than those in Asia. The agronomic benefits from transgenic crops also appear substantial: in the Philippines, the study referred to above estimates that the internal rates of return for the 3-in-1 GM rice range from 31 to 42 percent, even under conservative scenarios (Gonzales et al, 2008a). With more widespread adoption of modern varieties, these rates of return and benefit-cost ratios are likely to fall as yield growth tapers off, as has happened with the major cereals in India. Nevertheless, independent of any agronomic benefits that biofortified varieties may confer, the health benefits are substantial. What is also important is that biofortification fits a rural niche, in a way that is not easily met by other interventions.

The next step is to document costs and cost-effectiveness using ex post cost figures to replace the ex ante numbers discussed here. This will happen as biofortified varieties are disseminated; there are ongoing efforts to document costs with orange sweetpotato in Uganda and Mozambique so that the assumptions can be validated using field data.

It is important to guard against the risk of overinterpretation of the results from the ex ante cost analysis. The schematic presented in Figure 1 is useful for understanding the potential range in cost-effectiveness and the primary drivers of effectiveness. It suggests that the largest benefits at lowest costs are obtained in countries and crops-nutrients that fall in Quadrant A. However, if this argument is taken to its logical conclusion, it would be very difficult to justify investments outside South Asia, and in particular Sub-Saharan Africa where population densities are lower, and the availability infrastructure poorer than in Asia; clearly this would be an inappropriate inference. What is key is that all the benefit-cost ratios exceed unity by a substantial margin.

For the most part, these cost-effectiveness figures compare favorably to those of fortification (Horton, Alderman and Rivera, 2008a) and are robust to changes in key assumptions, although there are exceptions. As noted in Meenakshi et al (2007), there are some cases where biofortification does not enjoy a comparative advantage relative to fortification, notably in Latin America.

More research is necessary, however, before such comparisons can be made definitively. First, there is need for country-specificity to the fortification costs as well, since there is a wide variation across countries in these costs (as documented in Fiedler, 2007, who reviews some reasons for these). Second, comparisons must be made on a common methodological base, which is not possible at present. Taking into account both these factors will enable the development of a country-specific plan for an *optimal* mix of interventions—that includes biofortification, fortification and supplementation, for example—that will achieve the greatest reduction in micronutrient malnutrition for a given level of resources.

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