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Social Science & Medicine 66 (2008) 1797–1808

SOCIAL SCIENCE & MEDICINE

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Potential impacts of iron biofortification in India

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Available online 21 February 2008

Abstract

Iron deficiency is a widespread nutrition and health problem in developing countries, causing impairments in physical activity and cognitive development, as well as maternal mortality. Although food fortification and supplementation programmes have been effective in some countries, their overall success remains limited. Biofortification, that is, breeding food crops for higher micronutrient content, is a relatively new approach, which has been gaining international attention recently. We propose a methodology for *ex ante* impact assessment of iron biofortification, building on a disability-adjusted life years (DALYs) framework. This methodology is applied in an Indian context. Using a large and representative data set of household food consumption, the likely effects of iron-rich rice and wheat varieties are simulated for different target groups and regions. These varieties, which are being developed by an international public research consortium, based on conventional breeding techniques, might be ready for local distribution within the next couple of years. The results indicate sizeable potential health benefits. Depending on the underlying assumptions, the disease burden associated with iron deficiency could be reduced by 19–58%. Due to the relatively low institutional cost to reach the target population, the expected cost-effectiveness of iron biofortification compares favourably with other micronutrient interventions. Nonetheless, biofortification should not be seen as a substitute for other interventions. Each approach has its particular strengths, so they complement one another.

Keywords: Iron deficiency; Biofortification; DALYs; Impact assessment; India; Cost-effectiveness analysis

Introduction

Despite recent progress in the fight against hunger and malnutrition in many countries, global food and nutrition security is still a far-away goal. An estimated 820 million people in developing countries are undernourished (FAO, 2006). Many more suffer from specific deficiencies in certain micronutrients: 2 billion people are anaemic, many due to iron deficiency (WHO, 2007), 2 billion are iodine deficient and approximately 140 million children are vitamin A deficient (ACC/SCN, 2004). Unlike undersupply in terms of

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doi:10.1016/j.socscimed.2008.01.006

macronutrients, micronutrient deficiencies are not always apparent immediately, which is why the term 'hidden hunger' is also used. The health consequences can be severe, however, and include higher susceptibility to infectious diseases, impaired physical and cognitive development and increased mortality rates, especially among women and children due to their higher requirements. For instance, in India 85 million children and 26 million women are affected by iron deficiency anaemia (IDA); for men the number is estimated at 14 million.

While there is a clear correlation between hidden hunger and poverty, it is well-recognised that economic development and income growth alone are unlikely to control micronutrient malnutrition in the near future (Haddad, Alderman, Appleton, Song, & Yohannes, 2003). Direct micronutrient interventions – such as industrial fortification of foods, pharmaceutical supplementation or the promotion of dietary diversification – have been designed and implemented in many countries. Economic evaluations of such interventions show that, in most cases, benefit–cost ratios are favourable (Behrman, Alderman, & Hoddinott, 2004; Horton, 1999; Horton & Ross, 2003). Yet, except for iodised salt, their coverage and overall success in developing countries have been limited (ACC/SCN, 2004). For instance, supplementation programmes may have low compliance because of presumed side effects (Jefferds, 2002), their success may be limited by inadequate supply of supplements, cultural beliefs or the need to adhere to a daily regimen (Galloway et al., 2002), and those most in need of the supplements, i.e. women from poor and uneducated backgrounds, are often least likely to be covered by related health services (Pallikadavath, Foss, & Stones, 2004). Moreover, these programmes involve large recurring expenditures, which many developing countries cannot incur. Some of these problems also apply to food fortification programmes. Building on existing distribution channels for processed foodstuffs, institutional costs are lower, but coverage rates among the needy are often low, too, because the poor and malnourished typically consume locally produced foods and tend to purchase few processed products. In India, the percentage of wheat and rice that is marketed outside of the local community is only around 30–35% (Government of India, various issues), indicating that much of rural consumption is locally sourced.

Over the last 10 years, a new agriculture-based approach has evolved, in which staple food crops are bred for higher amounts of micronutrients in the edible parts. This strategy has been termed 'biofortification' (Bouis, 2002). Because the prevalence of micronutrient deficiencies is highest among the poor, who often cannot afford sufficient amounts of vegetables, fruits, and livestock products, biofortified staple crops may improve their nutrition and health status precisely because the micronutrients are embodied in the staples themselves. In principle, once such crops are developed and disseminated, they automatically become part of the food chain, with farmers reproducing biofortified seeds themselves for home consumption and local markets. However, since biofortified crops have hardly been released so far, their actual impacts remain uncertain, and a comprehensive methodology for ex ante impact assessment is not available.

There are two previous papers that deal with the potential economic impact of biofortification in some detail – both focus on the special case of Golden Rice in the Philippines. Dawe, Robertson, and Unnevehr (2002) used a regional food consumption data set to measure the potential nutritional effect of Golden Rice by analysing likely improvements in vitamin A intake. Thus, they analysed the impact from 'field to fork'. Yet, in the case of biofortified crops, it is necessary to go further and also map the impact from 'fork to fitness' (i.e. to physical and mental health). This was done by Zimmermann and Qaim (2004), who projected the actual health effects of Golden Rice by computing an expected reduction in the disease burden of vitamin A deficiency. However, they used highly aggregated national average vitamin A intake data, neglecting the distribution of individual intakes; use of average intakes can lead to a serious bias (Murphy & Poos, 2002).

The present article improves on the existing literature by developing a methodology to project the impact of iron biofortified crops all the way from 'field to fork to fitness', based on more comprehensive data and refined methodologies. To measure the burden of iron deficiency, we build on the concept of 'disability-adjusted life years' (DALYs). This burden is calculated with and without biofortification, so that the difference is the reduction in the disease burden through biofortification, expressed in the number of DALYs saved. Besides impact, we also analyse the cost-effectiveness of iron biofortification, which allows comparison of its efficiency with other public health interventions. This also addresses a research gap, as detailed cost-effectiveness estimates of biofortification with iron and zinc are not available (Ma et al., 2007).[1]

[1] Similar research as described here for iron biofortification has recently been carried out for zinc biofortification by Stein et al. (2007).

Empirically, we focus on iron biofortified crops in India. In the framework of the HarvestPlus Challenge Programme of the Consultative Group on International Agricultural Research (CGIAR), iron-rich rice and wheat varieties are being developed by conventional means (i.e. they are *not* genetically modified). These varieties will be released in India in the medium-term future. We assess their impact ex ante by using a nationally representative data set on food consumption and explicitly tying the distribution of dietary iron intakes to the prevalence of anaemia. A future shift in the distribution through biofortified varieties can then be translated into a quantifiable decrease in the prevalence of anaemia. While more details are provided later, we note here that this novel method has the advantage of not relying on external and often disputed definitions of intake requirements.

The next section discusses the DALYs framework. Then, the method is used to estimate the disease burden of iron deficiency (ID) in India – first without biofortification and then in a hypothetical situation where iron--rich rice and wheat is consumed. To account for uncertainty in the ex ante setting, two impact scenarios are considered – and also used for subsequent cost-effectiveness analyses. The last section concludes and discusses policy implications.

Methods

The DALYs framework

DALYs are quantified based on the severity and duration of a health outcome and expressed in common units that combine morbidity and premature mortality. The burden of a disease is expressed as the aggregated sum of years of life lost (YLL) due to cause-specific mortality and the sum of years lived with disability (YLD) (Murray & Lopez, 1996). YLD are normalised to be comparable to YLL by weighting the underlying health outcome according to the degree of disability it causes. Hence, the burden can be represented as:

$$\text{Burden of disease} = \text{DALYs}_{\text{lost}} = \text{YLL} + \text{YLD}_{\text{weighted}} \quad (1)$$

The so-called disability weights can range from 0 to 1, with 0 representing perfect health and 1 representing a health status equal to death.

In using the DALYs framework in a nutrition context, our focus is not on micronutrient deficiency *per se*, but on the adverse functional outcomes it causes. The incidence and severity of these outcomes can vary between population groups, because age and gender are important determinants of nutritional needs. Building on Murray and Lopez (1996) as well as the WHO-CHOICE project (www.who.int/choice), with some adaptations the disease burden of a particular micronutrient deficiency in a country or region can be calculated as:

$$\text{DALYs}_{\text{lost}} = \sum_j T_j M_j \left(\frac{1-e^{-rL_j}}{r}\right) + \sum_i \sum_j T_j I_{ij} D_{ij} \left(\frac{1-e^{-rd_{ij}}}{r}\right) \quad (2)$$

where T_j is the total number of people in target group j, and M_j is the mortality rate associated with the deficiency. I_{ij} is the incidence rate of functional outcome i in target group j, D_{ij} is the corresponding disability weight and d_{ij} is the duration of the outcome. Ill health can be transitory or permanent. For permanent health problems, d_{ij} equals the average remaining life expectancy L_j. The discount rate for future DALYs is r. As is common in the international health economics literature, we use a discount rate of 3% (c.f. Murray & Lopez, 1996; WHO, 2002; World Bank, 1993). However, unlike Murray and Lopez (1996), we do not include an age-weighting term because this implies an ethical value judgment and a social preference for certain age and gender groups (e.g. Williams, 1999).

DALYs lost measure the *annual* disease burden of the micronutrient deficiency. For using DALYs in a cost-effectiveness analysis, only new cases occurring in one particular year are counted, and all future losses in the form of long-term and permanent health problems are calculated, discounted and attributed to the underlying deficiency when the respective problem sets in. Therefore, the disease burden refers to the number of DALYs that are lost by each new age cohort.

The DALYs approach has the advantage of measuring health directly; thus, DALYs are not influenced by the earnings of individuals or, in international comparisons, by the productivity of nations. Hence, this method is more equitable than cost-of-illness or willingness-to-pay approaches, which use monetary quantification. The DALYs method, like the similar QALYs (quality-adjusted life years) method, is certainly not free of criticism (e.g. Anand & Hanson, 1998; Arnesen & Nord, 1999; Lyttkens, 2003). However, it captures the burden of disease in a transparent and comprehensive manner. In fact, it is the broader and more inclusive scope of DALYs that distinguishes them from the focus on productivity that characterises most alternative measures.

Calculating the disease burden of iron deficiency

ID is defined in relation to body iron stores; in its severe manifestation it can become IDA. IDA is a subgroup of anaemia that can also have causes other than insufficient iron intake (Nestel & Davidsson, 2002). Anaemia is classified as mild, moderate and severe. There is no robust evidence that mild anaemia is linked to tangible health problems (Rush, 2000; Stoltzfus, 2001). Murray and Lopez (1996) and subsequent studies attributed disability weights directly to moderate and severe IDA. Because IDA can have different health consequences, we use a more detailed approach and quantify the disease burden of each of the actual functional outcomes. These are (i) impaired physical activity (Hallberg & Scrimshaw, 1981), (ii) impaired cognitive development (Nokes & Bundy, 1997) and (iii) maternal mortality (c.f. Brabin, Hakimi, & Pelletier, 2001; WHO, 2007), which can have further consequences such as increased numbers of stillbirths and child deaths (Jones, Steketee, Black, Bhutta, Morris, & the Bellagio Group, 2003; Rush, 2000). Other functional outcomes have been associated with IDA, but here we consider only those for which there is a broad scientific consensus. We also disregard possible health outcomes ID without anaemia. Therefore, our results constitute a lower bound estimate of the total disease burden.

The disease burden of IDA is considered separately for moderate and severe manifestations and differentiated by the following target groups: (i) children ≤5 years old, (ii) children aged 6–14 years, (iii) women ≥15 and (iv) men ≥15. Impaired physical activity affects all four target groups, and we assume that the outcome persists until the group's upper age limit is reached. (Iron deficiency reduces blood haemoglobin levels, which reduces the oxygen carrying capacity of blood – and the ability to carry out physical activity; with improved iron status blood haemoglobin levels recover.) Impaired cognitive development only affects children ≤5 years, but in contrast to the impact on physical activity, the outcome is considered permanent. The average age of onset for impaired cognitive development is set at 6 months, which is when an infant's iron requirements can no longer be met by breast milk alone. For maternal mortality, it is assumed that 5% of all maternal deaths in India are due to IDA (Table 1). Approximately 30% of these cases result in stillbirths, and also the surviving infants are at a higher mortality risk, because they are not breastfed (Jones et al., 2003).

Disability weights were estimated for a typical developing country context, thus they are more specific than those used by Murray and Lopez (1996), which have been criticised for their assumed independence of the context in which the underlying disabling conditions occur (Allotey, Reidpath, Kouamé, & Cummin, 2003). Nevertheless, the range here, albeit more disaggregated, is in the aggregate equal to the values that have been used by Murray and Lopez. The information on functional outcomes, target groups and disability weights is summarised and referenced in Table 1. The approach used here is applied at a more disaggregate level than studies that look at world subregions as defined by the World Health Organization (e.g. Baltussen, Knai, & Sharan, 2004; Murray & Lopez, 1996); it also provides more details on the way DALYs are calculated, rather than taking them as a given.

Table 1
Functional outcomes of IDA, target groups and disability weights

Functional outcomes	Target groups (age in years)	Disability weights
Impaired physical activity (all individuals suffering from severe IDA)	Children ≤ 5, and 6–14	0.087
	Women ≥ 15, and men ≥ 15	0.090
Impaired physical activity (all individuals suffering from moderate IDA)	All	0.011
Impaired cognitive development (all individuals suffering from severe IDA)	Children ≤ 5	0.024
Impaired cognitive development (all individuals suffering from moderate IDA)	Children ≤ 5	0.006
Maternal mortality (5% of all maternal mortality)	Mothers	(1.0)
Stillbirths and child mortality (shares of IDA-related maternal mortality)	Children ≤ 5	(1.0)

Notes: This table is the outcome of a series of workshops that included nutritionists, medical doctors and agricultural and food economists both from the Indian subcontinent and abroad. These workshops were organised by the International Food Policy Research Institute (IFPRI) and held during 2003 and 2004. Details are discussed in the text; also see Stein et al. (2005).

The current disease burden of iron deficiency in India

The starting point for quantifying the current burden of ID is the prevalence of anaemia. In India, as in most other countries, anaemia prevalence rates are available for children and women of reproductive age, but not for adult men – whose prevalence rate is usually significantly lower than that of women; here we assume it is half. Because anaemia can have several causes, the rule of thumb is that 60% of the cases in children ≤5 years and 50% of all other cases can be considered as IDA due to insufficient iron intake (INACG, 2003). Our calculations for India were based on nationally representative data calculated from state-level surveys on the true prevalence of anaemia based on haemoglobin measurements (IIPS, 2000; NIN, 2003). The resulting prevalence rates for moderate IDA range from 3.7% for adult men to 27.5% for children under 6 years old, while that for severe IDA ranges between 0.5 and 3.2% (Table 2). These prevalence rates were transformed into incidence rates to avoid double counting in the DALYs calculations. The total number in the target age groups is based on demographic statistics (Census of India, 2001); life expectancies are taken from the Indian life table (http://www3.who.int/whosis/life/).

Inserting these data in Eq. (2), the burden of IDA can be calculated. Aggregating over all functional outcomes and target groups, the current annual burden amounts to 4.0 million DALYs lost, which underlines the severity of ID in India. Of this total, impaired physical activity and impaired cognitive development account for around 47% each, with the remaining 6% being due to maternal mortality and its consequences. This division indicates that alternative assumptions on the share of total maternal mortality attributable to IDA would hardly change the overall result. In terms of target groups, the biggest loss occurs among young children: they show the highest prevalence rates of IDA and are susceptible to permanent cognitive impairment. The total DALYs loss is similar to other studies that have been carried out at a more aggregate level or that consider the risk of suffering from the respective health outcomes rather than their prevalence (Table 3).

Table 2
Prevalence of IDA with and without iron biofortification of rice and wheat (%)

All India	Current prevalence rates of IDA[a]		Reduced rates with biofortification			
			Pessimistic scenario		Optimistic scenario	
Target group (age in years)	Moderate	Severe	Moderate	Severe	Moderate	Severe
Children ≤ 5	27.5	3.2	23.5	1.6	16.5	0.3
Children 6–14	15.6	0.8	12.9	0.4	7.0	0.1
Women ≥ 15	7.4	1.0	6.5	0.6	3.0	0.1
Men ≥ 15	3.7	0.5	3.3	0.3	1.5	0.0

[a] See explanation and sources in the text.

Table 3
Estimates of the disease burden of IDA in India in 2000 (DALYs lost)

Sources	Own calculations	Murray and Lopez (1996)[a]	WHO (2002)[b]
IDA (without mortality)	3.7 m	3.7 m	3.3 m
IDA (including all health outcomes)	4.0 m	–	–

[a] Projections for 2000.
[b] Derived from the WHO (2002) calculations for high mortality countries in SEAR-D by applying India's population weight.

Potential benefits of iron biofortification

Rice and wheat are the major staple foods in India. The average monthly per capita consumption in rural areas is 6.8 kg for rice and 4.5 kg for wheat (NSSO, 2000), but notable regional differences exist. Both rice and wheat are being bred for higher iron content at the International Rice Research Institute (IRRI) and the International Maize and Wheat Improvement Center (CIMMYT) within the HarvestPlus Programme (CIAT/IFPRI, 2004). After local adaptation, these varieties will be released by national programmes in India and other developing countries for dissemination.

Staple foods predominate in rural diets and account for 50–60% of all food expenditures among the poor in India (NSSO, 2000). Cereals account for the bulk of iron intakes (Sharma, 2006). The consumption of legumes has been declining over time, and meat products – which have higher bioavailable iron – are only consumed in very small quantities on average. While income growth has brought about some dietary diversification, budget shares of meat, eggs and fish are still less than 10% in rural areas (Sharma & Meenakshi, 2004). Given this, biofortified rice and wheat varieties appear to have the potential to improve iron intakes, and thus to lower the disease burden of IDA. Assumptions related to the nutritional and agronomic characteristics of iron-rich varieties and their acceptance by local farmers and consumers are based on interviews with international and local experts, supplemented with available literature sources. To account for uncertainty, we designed two impact scenarios – an optimistic and a pessimistic one, as described below.

Household data and current iron intake

In their analysis on the potential impacts of Golden Rice in the Philippines, Zimmermann and Qaim

(2004) used average national food intake data to establish the micronutrient status of average consumers. Other studies use national food balance data to assess the micronutrient status of populations (Wuehler, Peerson, & Brown, 2005). We improve on these approaches by using a nationally representative data set, with 120,000 household observations and consumption details for 140 food items (NSSO, 2000). Although for brevity our results are aggregated, the calculations are carried out at the household level. The Indian food composition tables (Gopalan, Rama Sastri, & Balasubramanian, 1989) were used to derive current iron intakes from all sources for each household in the data set. On average, over two-thirds of the energy and iron intakes of rural populations in India are accounted for by cereals – predominantly wheat and rice (Sharma, 2006).

Because data are available at the household rather than the individual level, we assume that individual food intake is proportional to relative energy requirements (i.e. the 'hunger' of each household member, although not their iron requirements). Based on the family structure, we then converted household food consumption into intakes per adult equivalent; from this we derived individual iron intakes.[2] Our assumption that food distribution within the household is unbiased deserves some further elaboration. Many studies for India have not shown conclusive evidence of gender bias within the household (c.f. Deaton, 1997; Subramaniam, 1996). A more nuanced view is offered by Haddad, Peña, Nishida, Quisumbing, and Slack (1996); however, they too do not find strong evidence of bias towards males except in North India. Thus, while there is a great deal of literature demonstrating gender bias in outcomes, it appears not to emanate from gender bias in intra-household food distribution.

A limitation of the data set is the absence of information on the provision of iron supplements to household members. Yet, the impact of India's supplementation programme is very low due to financial and institutional constraints (Kapil, 2003; Vijayaraghavan, 2002). Therefore, we do not expect this programme to significantly distort our results, and – while the programme may be more successful in covering pregnant women than young children – the only pregnancy-related health outcome of IDA (maternal mortality) contributes just 6% to the overall burden of IDA in India.

Improved iron intake

The extent to which biofortified rice and wheat can improve iron intakes in India will depend on the amount of iron that plant breeders get into the grain and the coverage that biofortified varieties will eventually have. Without biofortification, milled and polished rice contains about 3 parts per million (ppm) of iron and wheat about 38 ppm. The lead plant breeders at IRRI & CIMMYT reckon that ongoing breeding activities will increase the iron content by 100–167% in milled and polished rice (Barry, 2005), and by 20–60% in wheat (Ortiz-Monasterio, 2005). To put these numbers in perspective: for a 200 g consumption of milled rice per day, an *additional* 3 ppm of iron would translate into an additional 0.6 mg, and an *additional* 5 ppm would translate into an additional 1 mg of iron intake. In the case of wheat, a typical chapatti contains about 30 g of flour. Hence, the consumption of one chapatti translates into additional 0.23–0.68 mg of iron.

We use the lower and upper bounds of these ranges as the assumptions for our pessimistic and optimistic scenarios, respectively. These figures represent the iron content in rice and wheat prior to preparation and consumption. As the biofortified crops considered here are being developed by non-transgenic methods, the type of iron will be the same as in existing rice and wheat varieties, as will be the inhibitors and enhancers of iron absorption. Hence, there is no reason to assume that bioavailability or post-harvest losses of the additional iron would be different. Indeed, a recent controlled feeding trial in the Philippines suggests that the consumption of rice with an additional 3 ppm results in improved iron status. In that study, the subjects consuming the high-iron rice had a 17% higher iron intake than the control group, resulting in a modest increase in serum ferritin and total body iron: 'The greatest improvements in iron status were seen in those nonanemic women who had the lowest baseline iron status and in those who consumed the most iron from rice. Consumption of biofortified rice, without any other changes in diet, is efficacious in improving iron stores of women with iron-poor diets in the developing world' (Haas et al., 2005: 2823).

For the coming years, it is planned that the iron trait will be bred into more and more Indian rice and wheat varieties. To facilitate adoption among farmers, the

[2] To test the robustness of the adult equivalent weights, we regressed the households' iron consumption on household composition (age and gender groups) and used the coefficients of the independent variables to construct a different set of adult equivalent weights. The results were very similar to the weights derived from relative energy requirements (presumably because both energy and iron intakes are closely related to cereal intakes).

HarvestPlus strategy is to breed the micronutrient-rich trait into varieties that are agronomically superior. Because the adaptive research is carried out in collaboration with national programmes, biofortified varieties will reach farmers through established seed distribution channels. Seed prices for the farmers are expected to remain unaffected and, once obtained, farmers will be able to reproduce biofortified varieties themselves. Moreover, iron-rich rice and wheat looks and tastes the same as other varieties. Hence, consumer acceptance is not anticipated to be an issue. Taking into account previous experience with farmers' variety and seed replacement rates, the interviewed experts estimate that 20 years after release iron-rich rice could account for 20–50% of total rice production and iron-rich wheat 30–50% of total wheat production (Barry, 2005; Ortiz-Monasterio, 2005). Again, the lower and upper bounds of these ranges were used for our scenarios.[3] Because international rice and wheat trade in India is very small in relation to production (FAO, 2004), production shares are assumed to equal consumption shares at the national level.

Based on these assumptions, the improved iron intakes with biofortification (Fe^{imp}) can be computed for each adult equivalent as follows:

$$Fe^{imp} = Fe^{cur}_{tot} + \left(Fe^{cur}_{cr} \times \Delta Fe \times S\right) \quad (3)$$

where Fe^{cur}_{tot} is the current iron intake from all food sources, Fe^{cur}_{cr} is the current intake from the respective crop (rice or wheat), ΔFe is the proportional increase in the crop's iron content and S is the consumption share, i.e. the proportion of total household consumption from biofortified rice or wheat.

Health improvement

Increased iron intakes through biofortified crops are expected to improve the health status of deficient individuals (c.f. Haas et al., 2005). This link is conceptually shown in Fig. 1. Under the status quo, given the observed prevalence of IDA, the cut-off iron intake level, below which health problems are likely to occur, can be determined by using the cumulative distribution function of current iron intakes. We calculate internal cut-off levels separately for each target group and assume that the corresponding share of individuals with the lowest iron intakes, as derived by their respective adult equivalent weight, are those who are deficient. Since cut-off levels may vary regionally, due to different dietary patterns that influence iron bioavailability, we subdivide India into three dietary regions (rice eating, wheat eating and mixed diet).[4]

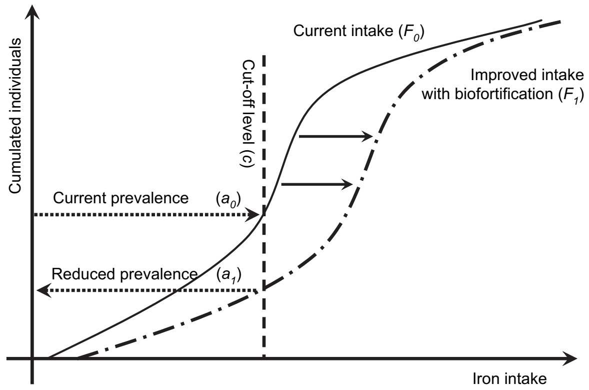

Fig. 1. Iron intake and IDA prevalence rates with and without biofortification.

The future consumption of biofortified crops will shift the cumulative distribution function of current iron intakes to the right. New, reduced prevalence rates with biofortification can then be inferred by determining the percentage of households with intakes below the internally established cut-off levels for deficiency. For each target group, given a current probability density function of intakes $f_0(i)$, and anaemia prevalence a_0, then $\int_0^c f_0(i)di = a_0$. That is, $F_0(c) = a_0$, where F_0 is the corresponding cumulative distribution function, and c is the cut-off level that is to be computed. Therefore, $c = F_0^{-1}(a_0)$. With biofortification, a new distribution of intakes F_1 may be derived using Eq. (3); clearly, by construction, F_1 lies everywhere to the right of F_0. The new (reduced) anaemia prevalence a_1 with biofortification (or any other intervention that improves intakes) is given by $a_1 = F_1(c)$.

This approach constitutes a considerable improvement over previous work in this field. For instance, Zimmermann and Qaim (2004) used a 'dose-response' function that relies on *average* micronutrient intakes and *external* requirements to determine the intake gap.

[3] Even under optimistic assumptions the amount of iron that is absorbed from biofortified food is not expected to cause problems of overdose or toxicity (c.f. Stein et al., 2005).

[4] Wheat eating region: Haryana, Punjab, Rajasthan, Uttar Pradesh, Uttaranchal, Chandigarh and Delhi; mixed diet region: Bihar, Jharkhand, Gujarat, Himachal Pradesh, Jammu & Kashmir, Karnataka, Madhya Pradesh, Chhatisgarh, Maharashtra, Dadra & Nagar Haveli and Daman & Diu; rice eating region: remaining Indian states and territories.

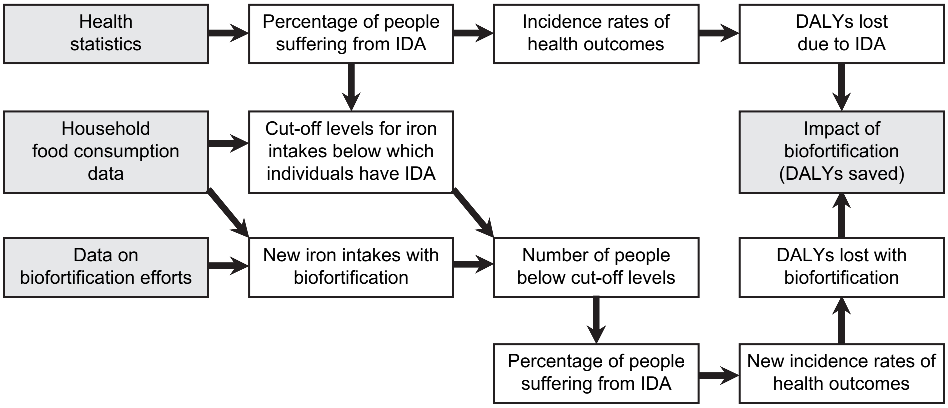

Fig. 2. Layout and rationale of method to calculate the impact of biofortification.

Yet, using average intakes may mask substantial variations between actual individual intakes, potentially introducing a serious bias (c.f. Murphy & Poos, 2002). Moreover, the quality of results hinges on the correctness of the micronutrient requirements used.[5] In our approach, we neither use average intakes nor externally set requirements. This is only possible when building on a representative household data set and is generally more demanding in terms of data analysis, but it is also more accurate and reliable. Although for graphic simplicity Fig. 1 only shows one cut-off, we apply the procedure separately for moderate and severe levels of IDA (whereby we avoid double counting).

Reduced IDA prevalence with iron biofortification of rice and wheat are shown in Table 2 for the two impact scenarios. For brevity, only the weighted results for India as a whole are displayed. The reduced rate of maternal mortality was derived from the current rate by applying the percentage decrease for severe IDA in women. With these reduced rates, the number of DALYs lost was re-computed to determine the remaining disease burden of ID in India with biofortification.

The whole layout of the procedure and the individual steps of the underlying calculations are illustrated in Fig. 2. The results and the number of DALYs saved through biofortification for all India and the three dietary regions are shown in Table 4. For illustrative purposes, we also calculated the impact of rice and wheat biofortification separately. It should be noted that simply adding up the separate results will overestimate the joint effect because of double counting: if biofortification of one crop already results in iron sufficiency for an individual, biofortifying the other crop would not have an additional benefit.

Table 4 shows that – even under pessimistic assumptions – biofortification of both rice and wheat may save 0.8 million DALYs every year, which is a 19% reduction of the current disease burden. Under optimistic assumptions the burden may be reduced by 58%. Although these results indicate that iron biofortification is unlikely to eliminate ID in India, the expected health benefits are sizeable. The scenario differences emphasize the importance of the iron content in the grain and the coverage rate, both of which can still be influenced through appropriate R&D policies. Rice biofortification alone produces higher benefits than wheat biofortification, mainly because of the higher consumption of rice relative to wheat, and because the current breeding activities are expected to increase the iron content in wheat less (in relative terms) than the iron content in rice. Also, the prevalence rates of IDA in the wheat eating region are somewhat higher. Hence, the deficiency is more severe and more difficult to overcome through iron biofortification of wheat.

[5] Zimmermann and Qaim (2004) use recommended dietary allowances (RDAs). But 'RDAs have been established as a target or goal for intake by an individual, and it can be assumed that individuals whose usual intakes are above the RDA are likely to be meeting their individual requirements […] However, the converse is not true. For this reason the RDA is not a useful reference standard for assessing an individual's intake' (IOM, 2000: 51). The correct reference intakes for assessing group diets are estimated average requirements (EARs), which represent 'the average daily nutrient intake level estimated to meet the requirement of half the healthy individuals in a particular life stage and gender group' (IOM, 2000: 3). Because 'some individuals with usual intakes below the EAR will meet their individual (lower-than-average) requirements. However, […] they will be counterbalanced by a similar number of individuals with intakes above the EAR, but below their individual (higher-than-average) requirements' (Barr, Murphy, & Poos, 2002: 785; also c.f. IOM, 2000).

Table 4
Potential health benefits of iron biofortification

Biofortified crop	Rice & wheat		Rice only		Wheat only	
Scenario	Pessimistic	Optimistic	Pessimistic	Optimistic	Pessimistic	Optimistic
All India (DALYs lost in status quo without biofortification: 4.0 m)						
DALYs lost with biofortification	3.2 m	1.7 m	3.5 m	2.5 m	3.7 m	3.0 m
DALYs saved through biofortification	0.8 m	2.3 m	0.5 m	1.5 m	0.3 m	1.0 m
Decrease relative to *status quo*	−19%	−58%	−12%	−38%	−7%	−26%
Rice eating regions (DALYs lost in status quo without biofortification: 1.1 m)						
DALYs lost with biofortification	0.8 m	0.3 m	0.8 m	0.3 m	1.1 m	1.1 m
DALYs saved through biofortification	0.3 m	0.8 m	0.3 m	0.8 m	0.0 m	0.0 m
Decrease relative to *status quo*	−29%	−73%	−29%	−72%	−0%	−4%
Wheat eating regions (DALYs lost in status quo without biofortification: 1.3 m)						
DALYs lost with biofortification	1.0 m	0.5 m	1.2 m	1.1 m	1.1 m	0.6 m
DALYs saved through biofortification	0.2 m	0.8 m	0.0 m	0.2 m	0.2 m	0.7 m
Decrease relative to *status quo*	−18%	−60%	−3%	−13%	−15%	−55%
Mixed diet regions (DALYs lost in status quo without biofortification: 1.6 m)						
DALYs lost with biofortification	1.4 m	0.9 m	1.5 m	1.0 m	1.5 m	1.3 m
DALYs saved through biofortification	0.2 m	0.7 m	0.1 m	0.6 m	0.1 m	0.3 m
Decrease relative to *status quo*	−13%	−46%	−9%	−35%	−5%	−17%

Cost-effectiveness of iron biofortification

Biofortification involves costs for R&D, including breeding and testing at CGIAR centres as well as in-country activities. To carry out a cost-effectiveness analysis, we assembled the specific cost estimates of iron biofortification from the HarvestPlus budget (CIAT/IFPRI, 2004) and the project leaders at IRRI & CIMMYT. Because iron content is one trait among many that breeders are working on, we only consider the cost that this one trait adds to the regular R&D efforts. The cost breakdown and time structure used in our calculations are given in Table 5. Because of the ongoing R&D activities, the true costs are still somewhat uncertain. Therefore, to be conservative, in the pessimistic scenario we *doubled* the figures of the budgetary projections. Overall, a 30-year time horizon is considered. The costs shown in Table 5 are annual averages.

The primary target countries for iron biofortification in the HarvestPlus Programme are India, Bangladesh and the Philippines for rice, and India and Pakistan for wheat. In our analysis for India, we used a share of the international breeding costs, which is equivalent to India's share of total rice and wheat production in these countries (FAO, 2004). In the optimistic scenario, international breeding costs were shared between primary and secondary target countries (Bangladesh, China, India, Indonesia, Philippines and Vietnam for rice and China, India and Pakistan for wheat). In-country efforts will be necessary both to crossbreed iron into additional local varieties and to promote their dissemination. After variety release, maintenance breeding will have to be carried out to preserve the iron trait in the germplasm. Apart from this, biofortification is not expected to involve major recurrent costs, which is one of its advantages vis-à-vis industrial fortification or pharmaceutical supplementation: for instance, if India's iron supplementation programme

Table 5
R&D costs and time structure for iron biofortification[a]

Biofortified crop	Rice only		Wheat only	
Scenario	Pessimistic	Optimistic	Pessimistic	Optimistic
Share of international R&D costs per year (US$)	1.1 m	0.2 m	1.1 m	0.3 m
Duration of international R&D (years)	8	6	9	7
In-country costs per year (US$)	0.8 m	0.5 m	0.8 m	0.5 m
Duration of in-country activities (years)	5	3	7	5
Maintenance costs per year (US$), until end of the 30-year period considered	0.2 m	0.1 m	0.2 m	0.1 m

[a] CIAT/IFPRI (2004) and information of the project leaders at IRRI & CIMMYT.

Table 6
Cost per DALY saved through iron biofortification (US$)

Scenario	Pessimistic	Optimistic
Iron biofortified rice & wheat	5.39	0.46
Iron biofortified rice only	3.96	0.30
Iron biofortified wheat only	8.71	0.63

were scaled up to reach 50% of its target population, the cost of the tablets alone – without distribution – would amount to US$5.2 million *each* year (based on Kapil, 2004).

Once biofortified crops are released, with more iron-rich rice and wheat varieties becoming available, over time adoption rates will increase. In calculating health benefits, we assume a linear diffusion curve until the coverage rates mentioned in the previous section will have been reached after 20 years. Dividing the discounted monetary costs by the discounted number of DALYs saved yields an average cost per DALY, which we take as our measure of cost-effectiveness. The results are summarised in Table 6. Depending on the assumptions made, the cost per DALY saved ranges from 30 cents to US$8.70. Cost-effectiveness is higher for rice biofortification alone than it is for combined rice and wheat biofortification, partly because of the above-mentioned higher consumption of rice relative to wheat.

The World Bank (1993) describes costs per DALY saved of US$1–3 as 'most cost-effective' and costs less than US$25 as 'remarkably low' (in 2004 dollars these costs are US$ 1.5–4.3 and US$ 36, respectively; c.f. BLS, 2005). Interventions that cost between US$50–150 per DALY saved are classified as 'highly cost-effective' (in 2004 dollars the threshold is US$ 72–217). Hence, our results suggest that iron biofortification of rice and wheat is likely to be very cost-effective. Moreover, biofortification appears to be more cost-effective than iron supplementation programmes (US$12.8 per DALY saved, US$14.8 in 2004 dollars) or iron fortification of food (US$ 4.4 per DALY saved, US$5.1 in 2004 dollars) (Gillespie, 1998).

Conclusions

Controlling micronutrient malnutrition through crop breeding is a relatively new approach, and very little information is available on the implications and the economic outcome – which is a gap we attempt to bridge in this paper. While innovations in agriculture usually aim at yield increases or input savings, in the case of biofortification the objective is improved health. We put forward a consistent and comprehensive framework for the economic analysis of this new micronutrient intervention at the micro level. In particular, we have refined the method of disability-adjusted life years (DALYs) to quantify potential health benefits and the cost-effectiveness of iron biofortification. Empirically, we have analysed ex ante the impacts of iron-rich rice and wheat varieties in India. Building on a large household food consumption data set, a cumulative distribution function of iron intakes has been derived to explicitly tie food consumption to adverse functional outcomes. Our findings can help to better understand the potential effectiveness and efficiency of iron biofortification compared to other public health interventions.

According to our calculations, the current disease burden of iron deficiency (ID) in India amounts to 4 million DALYs lost each year. Even in a pessimistic scenario, iron biofortification of rice and wheat can reduce this burden by 19%, and the cost per DALY saved is US$5.39. In an optimistic scenario, the disease burden of ID may be reduced by 58%, and the cost per DALY saved would decline to 46 cents. Because some impact parameters are hard to anticipate ex ante, these results should be treated as preliminary. The differences between the two scenarios reflect this uncertainty, but they also highlight where appropriate policies can improve the results: beside the actual amount of iron that plant breeders can get into the grain, the coverage of biofortified varieties in national production and consumption is an important element, which can still be influenced by national promotion programmes.

The cost-effectiveness of iron biofortification compares favourably with other iron interventions such as supplementation and fortification. The main reason for this is that the institutional cost of reaching the target population through biofortification will be relatively low. Once iron-rich rice and wheat varieties have been developed and disseminated, a continuous benefit stream is expected without major recurrent costs. Nonetheless, from a policy point of view, biofortification cannot be seen as a substitute for other micronutrient interventions. Each approach has its particular strengths and weaknesses which complement one another. The overarching food security goal is to improve and diversify the diets of the poor through poverty reduction on a broader scale. However, until this long-term objective is reached, our findings suggest that biofortification represents an economically viable intermediate intervention to reduce the prevalence of IDA. Basic breeding work to increase iron, zinc and beta-carotene contents in different staple food crops is currently ongoing in CGIAR centres. Similar research is being supported under the Grand Challenges in Global Health Initiative. Thus, soon developing countries will have access to micronutrient-rich lines, which they can use in their national breeding programmes. With more information becoming available, further economic studies are needed to analyse the potentials and constraints in specific situations and at the macro level.

Acknowledgments

We gratefully acknowledge financial support of the German Research Foundation (DFG) and HarvestPlus. The authors thank Rekha Sharma for sharing her computations and for assistance with the NSS data. They also thank Gerard Barry and Ivan Ortiz Monasterio for helpful discussions and comments.

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