Potential Impacts of
Iron Biofortification in India

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Abstract

Iron deficiency is a widespread nutritional problem in developing countries, causing impaired 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 crops for higher micronutrient content, is a relatively new approach. We propose a methodology for ex-ante impact assessment of iron biofortification, which builds on disability-adjusted life years (DALYs) and a large household data set. Our analysis of iron-rich rice and wheat in India indicates sizeable potential health benefits. The cost-effectiveness of iron biofortification compares favourably with other interventions.

Keywords: biofortification, plant breeding, iron deficiency anaemia, health benefits, DALYs, cost-effectiveness, cost-benefit analysis, India.

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1 Introduction

Despite recent progress in the fight against hunger and malnutrition in some countries, global food and nutrition security is still a far-away goal. An estimated 800 million people in developing countries are undernourished and do not eat enough food to meet their energy requirements (FAO, 2004a). Many more suffer from specific deficiencies in certain micronutrients: 4-5 billion people are iron deficient, 2 billion are iodine deficient and approximately 140 million children are vitamin A deficient (ACC/SCN, 2004). Unlike undersupply in terms of 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.

While there is a positive 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 et al., 2003). A recent assessment of the role of agriculture in achieving the Millennium Goals has shown that even if economic growth increases above a business-as-usual scenario, the target of halving malnutrition by 2015 will not be met – which bodes ill for 'hidden' micronutrient malnutrition (c.f. Rosegrant et al., 2006). Direct micronutrient interventions – such as industrial fortification of foods, pharmaceutical supplementation and the promotion of dietary diversification through nutrition education – have been designed and implemented in many countries. Economic evaluations show that, in most cases, benefit-cost ratios are favourable despite differences in efficacy and institutional requirements to reach target groups (Behrman et al., 2004; Horton and Ross, 2003; Horton, 1999). Yet, except for iodised salt, their coverage and overall success in developing countries have been limited (ACC/SCN, 2004).[1]

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 grain, roots and tubers. This strategy has been termed 'biofortification' (CIAT/IFPRI, 2004; Bouis, 2002; Bouis et al., 2000). Because the prevalence of micronutrient deficiencies is highest among the poor, who often cannot afford sufficient amounts of pulses, vegetables, fruits, and livestock products, biofortified staple crops may improve their nutrition and health status precisely because the micronu-

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[1] For instance, iron supplementation programmes have low compliance (because of side effects) and vitamin A supplementation programmes often have low coverage because of few points of contact with the target group. These programmes also involve large recurring expenditures, which many developing countries cannot incur. For fortified foodstuffs as well, the main problem is reaching those in need, because the poor and malnourished tend to purchase few mill-processed products and typically consume locally-produced foods.

trients are embodied in the staples themselves. In principle, once such crops are developed and successfully 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.

Most assessments of impact of agricultural technologies focus on changes in producer and consumer surplus that arise from a rightward shift in the supply function (Alston *et al.*, 1995). Multiplier effects on livelihoods and poverty are sometimes captured through multimarket or general equilibrium models. In the case of biofortification, which uses agriculture as a *public health* intervention, the impact pathway is different. While nutrient-dense traits may piggyback on agronomically superior varieties, biofortification does not shift the supply function *per se*. At the same time, there may be no shift in the demand curve either. Especially minerals like iron or zinc are invisible in the crops, so that they constitute credence rather than search or experience attributes. But even if consumers were able to identify biofortified varieties, it may not be appropriate to treat micronutrients as quality traits that shift the demand curve out, because the ability and willingness to pay more for micronutrient-dense crops is likely to be limited among the poor. Rather, direct benefits accrue to health from the consumption of biofortified staple foods, and it is these health benefits that need to be captured.

There are two main papers that deal with the potential economic impact of biofortification in some detail – both focus on the Philippines and on the more special case of genetically engineered Golden Rice. Dawe *et al.* (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. In doing so, they analysed the impact from 'field to fork'. However, 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 actual distribution of individual intakes. As the prevalence of nutrient deficiencies depends on the shape and variation of the intake distribution, use of average intakes can be associated with a serious bias (Murphy and Poos, 2002; Murphy *et al.*, 2002).

The present article improves on the existing literature by developing a methodology to project the impact of biofortified crops from 'field to fork to fitness', based on more comprehensive data, thus combining the strengths of the two previous studies. To measure health, we build on 'disability-adjusted life years' (DALYs) – an approach which is common in health economics but has hardly been used in the agricultural economics literature up till now. The disease burden of micronutrient malnutrition is expressed in the number of DALYs lost. This 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. In addition

to this impact, we also analyse the cost-effectiveness, which allows comparison of the efficiency of biofortification with other public health interventions. However, since biofortification requires breeding investments, it might also be interesting to compare their social profitability with other agricultural research and development (R&D) investments, whose benefits can usually not be expressed in terms of DALYs saved. Therefore, we also discuss ways of monetising the health impacts of biofortification, in order to conduct a standard cost-benefit analysis.

Empirically, we focus on iron biofortification in India, where over 50% of women and 74% of children are anaemic (IIPS, 2000), largely due to insufficient intake of bioavailable iron.[2] 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 and tested, which will be released in India in the medium-term future.[3] We assess their impact by using a nationally-representative data set on food consumption (with 120,000 households) and explicitly tying the distribution of iron intakes (from all sources) to the prevalence of anaemia. A 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 that this novel method developed here has the advantage of not relying on external and often disputed definitions of intake requirements to establish the impact on the magnitude of micronutrient deficiency. Given that iron biofortified crops are not yet on farmers' fields, the analysis takes an ex-ante perspective.

The next section discusses the DALYs framework in comparison with alternative health measures. Subsequently, the method is used to estimate the disease burden of iron deficiency (ID) in India; first without biofortification in section 3, and then in a hypothetical situation where iron-rich rice and wheat varieties are consumed in section 4. To account for uncertainty in the ex-ante setting, two impact scenarios are considered – one with optimistic and the other with more pessimistic assumptions. These scenarios are also used for cost-effectiveness and cost-benefit analyses in sections 5 and 6. The last section concludes and discusses policy implications.

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[2] Bioavailability is the fraction of dietary iron that is absorbed from food, with the absorption being greater from meat-based diets. (The recommended dietary allowance for Indian males is 28 mg per day per person, which reflects the poor bioavailability of iron in the average Indian diet.)

[3] In the HarvestPlus Programme, the focus is on exploiting variation in iron content to identify high iron lines and to breed these into popularly cultivated varieties. An alternative strategy of breeding for lower phytate content also exists, as phytates inhibit the absorption of dietary iron. However, this is not being pursued in HarvestPlus, as phytates may have an important role to play in the metabolism of the plant (Bouis *et al*. 2000). The iron-dense varieties currently being developed are conventional varieties, that is, they are *not* genetically modified. This is a major difference to the better known example of 'Golden Rice', which is biofortified with provitamin A through genetic engineering.

2 Measuring Health

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 in a country 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*). *YLD* are normalised to be comparable to *YLL* by weighting the underlying health outcome according to the degree of disability that it causes. Building on Murray and Lopez (1996), this rationale can be represented thus:

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

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.[4] In using the DALYs framework in a nutrition context, our focus is not on micronutrient deficiency *per se*, but on the adverse functional outcomes that are caused by such deficiencies. The incidence and severity of these functional outcomes can vary between population groups, because age and gender are important determinants of nutritional needs. Hence, the disease burden of a particular micronutrient deficiency in a country or region can be calculated as:

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

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,[5] 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.

DALYs lost measure the *annual* disease burden of the micronutrient deficiency. 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 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 several advantages. DALYs measure health directly and, thus, are not influenced by the earnings of individuals or, in international comparisons, by the pro-

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[4] Hence, unlike more ad hoc measure that only focus on mortality – the use of which may attract the attention of policy makers and divert resources from non-fatal but more widespread health problems – DALYs capture the whole scope of disease from mild debility to mortality.

[5] Health statistics usually express the frequency of ill health conditions in terms of prevalence rates, which are stock figures. In contrast, the incidence rate (which is used in the DALYs formula) is a flow figure; it does not reflect how many people are ill, but how many people become ill in a given period of time. Yet, together with the information on the duration of a condition (which also enters the DALYs formula), each of these two figures can be converted into the other.

ductivity of nations. Therefore this method is more equitable than cost-of-illness or willingness-to-pay (WTP) approaches, which aim at approximating the impact of ill health through monetary quantification. In the case of cost-of-illness analyses the income of individuals or nations contributes to the overall 'cost' of an illness via the opportunity cost of time. Similar outcomes are possible with WTP approaches: the more individuals or societies earn, the more they are willing to pay for health. This means the same disease is rated more severe if it affects patients with high incomes or if it occurs in nations with high per capita incomes. However, in a developing country context, one reason for low incomes may be found in people's low nutrition and health status (World Bank, 2006; Sachs *et al.*, 2004; Strauss and Thomas, 1998). Fogel (2004a/b) has shown how, historically, better nutrition contributes to economic growth, both through immediately increasing work output (thermodynamic effect), but also through enlarging health endowments over time from one birth cohort to another (physiological effect) – which is how he explains 30% of the British growth in per capita income over the past two centuries.

As a measure of deprivation, DALYs have other intuitively appealing properties. For example, a deterioration in the health of an individual, or an increase in the number of individuals with a given outcome results in more DALYs lost. Similarly, relative deprivation is implicit in the disability weights: the more sever the ill-health, the higher the number of DALYs lost. These features are in contrast with those of other approaches used in the health economics literature – such as the cost-of-illness and WTP approaches. For example, if in cost-of-illness studies the productivity loss that is caused by a disease is determined, the loss is 100% once the individual is bedridden; further deteriorations of her health cannot be taken into account. In the case of WTP studies, if a poor person or nation (with a low capacity-to-pay) experiences a health loss while a healthier and richer person or nation (with a correspondingly high WTP) averts a similar loss, the measure may even indicate an improvement in overall health. Hence, DALYs are a better measure of poor health. And while it is possible to address the equity problems of cost-of-illness and WTP approaches to some extent, e.g. through using standardised values for quantifying the opportunity cost of time or the value of preventing a disease, similar results may be obtained through the use of DALYs – with the additional benefit of explicitly quantifying the burden of ill health. While cost-of-illness and WTP analyses quantify the *economic* burden of ill health directly, the information requirements are often too great to permit the kind of disaggregated analysis attempted here. DALYs measure the actual amount of ill health – i.e. they quantify the *disease* burden.

There are, of course, some limitations of the DALYs method as well. For instance, the discounting of future life years has been criticised (Lyttkens, 2003; Anand and Hanson, 1998). With discounting, present lives become relatively more valuable; this can serve to justify interventions that benefit the present generation at the expense of future generations. In short, discounting can be deemed inequitable. Nevertheless, we support the view that for policy-related questions discounting makes sense and apply a discount rate of 3% to both costs and

DALYs. This is a common approach in an international context (World Bank, 1993; Murray and Lopez, 1996; WHO 2002).[6] However, unlike Murray and Lopez (1996), we do not include age-weighting terms. Age-weighting increases the burden of a disease if a disabling condition affects young, productive adults rather than infants or the elderly; it also weighs the life and health of women higher than the life and health of men. Because this implies an ethical value judgment and a social preference for certain age and gender groups, it has been criticised (e.g., Williams, 1999). Yet, even without age-weighting, age enters the DALYs calculations through the remaining life expectancy of affected individuals. And the impact of the functional outcomes of ID at different ages is taken account of through the definition of the different target groups and the respective disability weights.

A more general criticism of DALYs is that the method focuses only on the health of individuals that are directly affected and fails to take account of formal and informal health care costs or the anxiety of people close to them (Lyttkens, 2003).[7] Furthermore, DALYs can be seen to put a value on human life – whether implicitly or explicitly – and to express the value simply as a positive function of health, thus failing to capture all dimensions of life (Arnesen and Nord, 1999; Groce *et al*., 1999). Yet, as discussed before, all measures of ill health suffer from one limitation or another. DALYs – though not free of limitations – capture the burden of a disease in a transparent and equitable manner. In fact, it is the broader and more inclusive scope of the DALYs approach that distinguishes it 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 iron deficiency anaemia (IDA). IDA is a subgroup of anaemia that can also have causes other than insufficient iron intake, including hookworms or malaria (Nestel and 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 attribute disability weights directly to moderate and severe IDA. Because IDA can have different 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 and Scrimshaw 1981), (ii) impaired cognitive development (Nokes and Bundy, 1997) and (iii) maternal mortality (c.f. Brabin *et al*., 2001; WHO, 2003), which can lead to further negative outcomes such as increased numbers of stillbirths and child deaths, the latter occur due to the lack of breastfeeding and care caused by the death of the

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[6] To test the sensitivity of the results to changes in the discount rate, we also ran all calculations without discounting of health benefits. As expected, both the absolute health costs and the benefits of biofortification increase. Detailed results can be made available upon request.

[7] However, studies using other approaches to quantify the burden of a disease do not necessarily include these costs, either. For instance, Horton and Ross (2003) only estimate the productivity losses that are caused by ID.

mother (Rush, 2000; Jones *et al.*, 2003). Other functional outcomes have been associated with IDA, but here we consider only those for which there is a broad scientific consensus in the form of meta analyses.[8] Likewise, we also disregard possible health outcomes of mild anaemia and of ID without anaemia. Therefore, our results constitute a lower bound of the total disease burden of ID.

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 outcome persists until the group's upper age limit is reached. Impaired cognitive development only affects children ≤ 5, but the outcome is 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). Ap-

Table 1. Functional outcomes of IDA, target groups and disability weights[a]

Functional outcomes	Target groups (age in years)	Disability weights
Impaired physical activity (100% of individuals suffering from severe IDA)	Children ≤ 5, and 6-14	0.087
	Women 15+, and men 15+	0.090
Impaired physical activity (100% of individuals suffering from moderate IDA)	All	0.011
Impaired cognitive development (100% of individuals suffering from severe IDA)	Children ≤ 5	0.024
Impaired cognitive development (100% of 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: [a]The functional outcomes are based on the literature as discussed in the text. The disability weights are based on Murray and Lopez (1996) and adapted to the particular context. All these findings are outcomes of a series of workshops that included nutritionists, medical doctors and agricultural 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. For more details see Stein *et al.* (2005).

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[8] Some studies have suggested that stunting is a functional outcome of ID (e.g., Latham *et al.*, 1990), but a recent meta-analysis did not establish a significant cause-effect relationship (Ramakrishnan *et al.*, 2004).

proximately 30% of these cases result in stillbirths and also the surviving infants are at risk of higher than average mortality, because they are not breastfed (Jones *et al.*, 2003). A direct association of perinatal mortality with IDA was not considered in the present analysis, because the scientific basis for such a causal link was deemed too weak (c.f. Stein *et al.* 2005). Disability weights for non-fatal functional outcomes were estimated for a typical developing country context, thus they are more specific than those of the GBD, which have been criticised for their assumed independence of the context in which disabling conditions occur (Allotey *et al.*, 2003). Nevertheless, the range here is similar to the values that have been used by Murray and Lopez (1996). The information on functional outcomes, target groups and disability weights is summarised in Table 1.

3   The Current Disease Burden of Iron Deficiency in India

The starting point for quantifying the current disease burden of ID, without biofortification, is the prevalence of anaemia. In India, as for most other countries, anaemia prevalence rates are available for children and women of reproductive age, but not for adult men (IIPS, 2000; NIN, 2003). The prevalence of anaemia in men is usually significantly lower than in women; here we assume it is half of that of women. Because anaemia can have several causes, the rule of thumb is that 60% of the cases in children under six years old and 50% of all other cases can be considered as IDA due to insufficient iron intake (INACG, 2003). Our calculations for India use state-level data on the true prevalence of anaemia, weighted by population numbers to derive average national figures. The resulting prevalence rates for moderate IDA range from 3.7% for adult men to 27.5% for children under six years old, while that for severe IDA ranges between 0.5% and 3.2% (Table 2). As explained above, 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 official demographic statistics (Census of India, 2001) and life expectancies are taken from the Indian life table (WHO, 2001a).

Inserting these data in equation (2), the disease burden of IDA can be calculated.[9] Aggregating over all functional outcomes and target groups, the current annual burden amounts to

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[9] For illustration of the calculations with rounded figures: if the incidence of impaired physical activity due moderate IDA among the 230.5 million children aged 6-14 years in India is 0.0184 (derived from a prevalence rate of about 0.16), this means there are about 4.24 million new cases of this health outcome in the target group each year. The assumption is that the physical activity of these children is impaired when they enter the target group (because they were already anaemic in the previous target group, even though some of the previous target group recovered and are not counted any longer) and remain so until they leave it. Of course there will be some individuals who recover from IDA before they leave the target group, while others will suffer from IDA even after they left the target group (but are not yet counted there). Hence, each of these 4.24 million cases lasts 9 years on average (from age 6-14 years, inclusive), i.e. there are about 38.2 million accumulated years during which children aged 6-14 suffer impaired physical activity due to moderate IDA. Yet, the disability weight for this health outcome is 'only' 0.011, i.e. the health and the functioning of the affected children is only reduced by

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

Notes: [a]Derived from IIPS (2000) and NIN (2003). Both data sources build on national community surveys, which used actual blood sampling and followed quality control procedures.

4.0 million DALYs (i.e. healthy life years) lost, which underlines the severity of ID in India. Of this total disease burden, impaired physical activity and impaired cognitive development account for around 47% each, with only 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 are unlikely to change the overall result. This may also explain differences between our results and those of other studies that have been carried out at a more aggregate level (Table 2) or that consider the *risk* of suffering from the respective health outcomes rather than their prevalence; our estimates are more conservative. 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; all future DALYs lost due to impaired cognitive development by a child are summed up and counted at the age of 6 months.

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

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

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

about 1%. Consequently about 420,000 accumulated *healthy* life years are lost and, after discounting, this translates into about 370,000 DALYs lost annually due to this health outcome in this target group.

## 4   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 (Figure 1). In some northern states wheat consumption is higher than rice consumption, while in other states, especially in the south, rice is the predominant staple food. 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) in 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 to 60% of all food expenditures among the poor (NSSO, 2000). Cereals account for the bulk of the iron intakes in the diet (Sharma, 2006). While legumes are also rich in iron, their consumption has seen a steady decline over time. Diets are largely vegetarian and the consumption of meat products – which have higher bioavailable iron – is limited. While income growth has brought about some dietary diversification, it has been of limited magnitude; budget shares of meat, eggs and fish, for example, are less than 10% in rural areas, a figure which has not increased much over time (Sharma and Meenakshi, 2004). Thus, reliance on cereals as a primary source of dietary iron is likely to continue. Given this, biofortified wheat and rice 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 breeders, agronomists and social scientists, 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 *et al*., 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 were carried out at the household level, so that regional and social heterogeneity in food consumption patterns was accounted for.

The Indian food composition tables (Gopalan *et al*., 1989) were used to derive current iron intakes from all sources for each household in the data set. Because data are only available at the household and not the individual level, we assumed individual food intake was proportional to relative energy requirements. Based on the family structure, we then converted household iron intakes into intakes per adult equivalent. Obviously, the underlying assumption is that the distribution of food within the household is unbiased. The literature is not conclusive
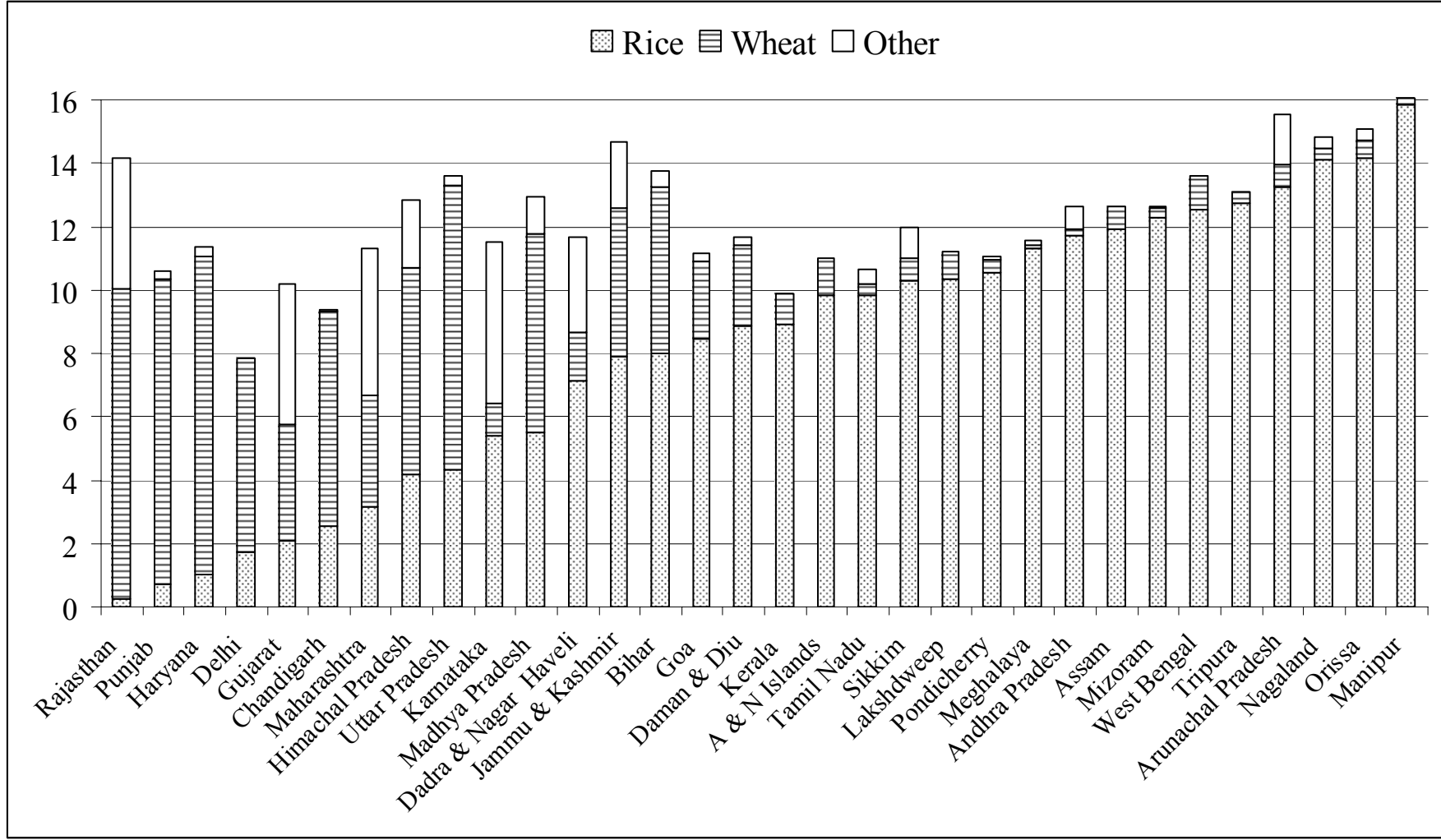
Source: Own presentation based on data from NSSO (2000).

Figure 1. Cereal consumption (kg capita^{-1} month^{-1}) in rural India, 1999/2000

on this issue but tends to reject the existence of general gender discrimination (Haddad *et al*., 1996). The evidence for India also tends to reject intra-household inequality in food allocation (Deaton, 1997: 231-238).[10] To take account of regional dietary differences within India, we defined and analysed three dietary regions separately (rice eating, wheat eating and mixed).[11] This disaggregation allows for higher bioavailability of iron from rice, compared with that from wheat. (Much of the wheat is consumed as whole meal, which has a higher phytate content than milled and polished rice.)[12]

A limitation of the data set is the absence of information on the provision of iron supplements to household members, because India has a long-standing supplementation programme to cover young children and pregnant women. Yet, the impact of this 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 indeed, while the programme may be more successful in covering pregnant women than young children with iron tablets, the only pregnancy-related health outcome of IDA (maternal mortality) contributes just 6% to the overall disease 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 can get into the grain and the coverage that biofortified varieties will eventually have in the country. 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 and CIMMYT reckon that ongoing breeding activities will increase the iron content by 100-167% in milled and polished rice (G. Barry, 2005, personal communication), and by 20-60% in wheat (I. Ortiz Monasterio, 2005, personal communication). 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 iron compounds will be the same as in existing rice and

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[10] Nevertheless, to test the robustness of the adult equivalent weights, we also 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 adult equivalent weights derived from relative energy requirements (presumably because both energy and iron intakes are closely related to cereal intakes).

[11] Our wheat eating region comprises the states of Haryana, Punjab, Rajasthan, Uttar Pradesh, Uttaranchal, Chandigarh, and Delhi; our mixed diet region (where also coarse cereals can be a common staple) comprises Bihar, Jharkhand, Gujarat, Himachal Pradesh, Jammu & Kashmir, Karnataka, Madhya Pradesh, Chhatisgarh, Maharashtra, Dadra & Nagar Haveli, and Daman & Diu; our rice eating region comprises the remaining Indian states and territories.

[12] We do not consider the question of absorption-enhancers such as vitamin C. Our estimates thus provide a lower limit of the impact of biofortification – if diets diversify to include more sources of vitamin C, the impact on iron status may be much greater.

wheat varieties, and there is no reason to assume that bioavailability or post-harvest losses of the additional iron would be different.[13] Indeed, a recent controlled feeding trial in the Philippines suggests that the consumption of rice with an additional 3 ppm did result in improved iron status (Haas *et al.*, 2005).

For the coming years, it is planned that the iron trait will be bred into more and more Indian rice and wheat varieties. The HarvestPlus strategy is to breed micronutrient-rich and agronomically superior varieties that will facilitate adoption among farmers. Achieving this goal may be facilitated if the breeding also improves iron density in the seeds and iron provision of the plants themselves (Bouis *et al.*, 2000). Because the adaptive research is carried out in collaboration with national programmes as part of ongoing public breeding efforts, biofortified varieties will reach farmers through established seed distribution channels. Seed prices should 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, in particular regarding adoption and coverage of high yielding varieties (Evenson and Gollin, 2003), 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. Again, the lower and upper bounds of these ranges were used as assumptions in our scenarios. Because international rice and wheat trade in India is very small in relation to production (FAO, 2004b), 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:

$$(3) \qquad Fe^{imp} = Fe_{tot}^{cur} + \left(Fe_{cr}^{cur} \cdot \Delta Fe \cdot S\right)$$

where Fe_{tot}^{cur} is the current iron intake from all food sources, Fe_{cr}^{cur} 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 rice or wheat consumption from biofortified varieties.

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 Figure 2. Under the status quo, given the prevalence of IDA, the corresponding iron intake level may be determined by inverting the cumulative distribution function of iron intakes; we term this the cut-off level in Figure 2. In other words, we calculate internal cut-off levels from current IDA

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[13] Overall, the bioavailability of non-heme iron found in plant-based foods is relatively low, depending on various inhibiting and enhancing factors. The reasonable assumption used here is simply that each unit of iron has the same bioavailability with and without biofortification.

prevalence rates for each target group and for each dietary region 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. The consumption of biofortified crops shifts 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. That is, for each target group, given a current probability density function of intakes $f_0(i)$, and anaemia prevalence a_0, we make the reasonable assumption that $\int_0^c f_o(i)di = a_0$.

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 equation (3); clearly, by construction, F_1 first-order stochastically dominates F_0. The new (reduced) anaemia prevalence a_1 with biofortification (or any other intervention that results in a rightward shift in the distribution of intakes) is given by $a_0 = F_1(c)$.
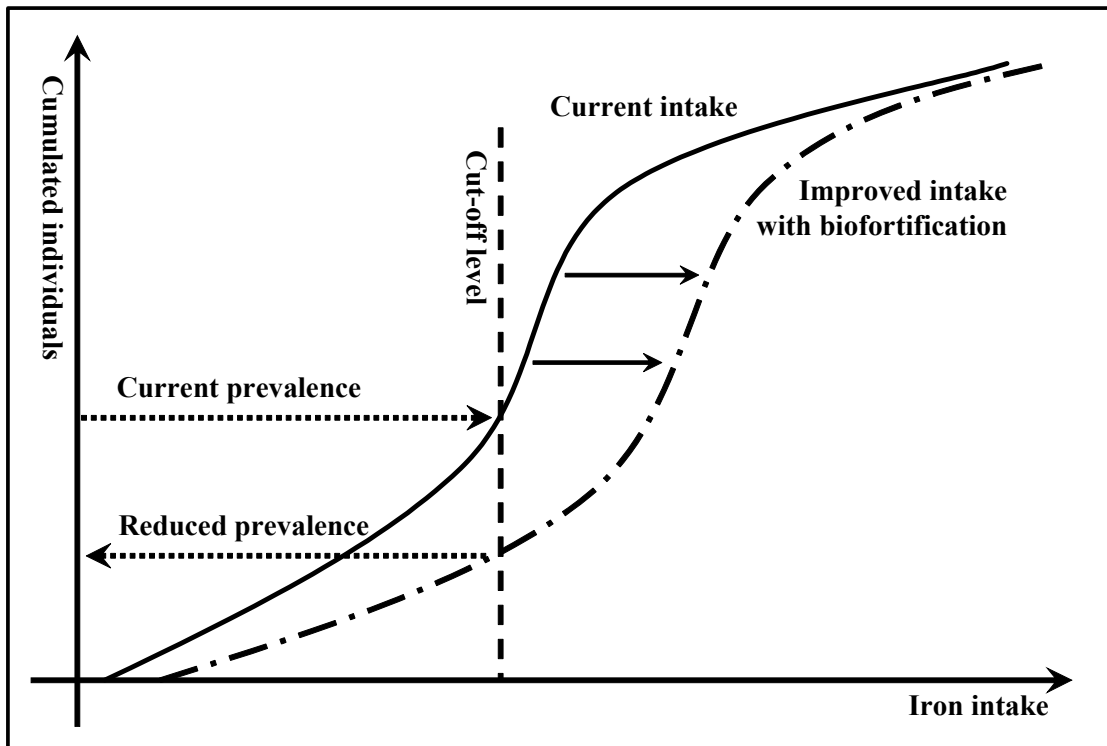
Figure 2. Iron intake and IDA prevalence rates with and without biofortification

This approach is an improvement over previous work in this field. For instance, Zimmermann and Qaim (2004) use a 'dose-response' function that relies on *average* intakes and *external* requirements to determine the shortfall of the micronutrient intake. While using average intakes may cover substantial variations between the actual individual intakes and introduce a serious bias (c.f. Murphy and Poos, 2002), the quality of the results also hinges on the

correctness of the requirements used.[14] 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 labour-intensive, but it is also more accurate and reliable. Although for graphic simplicity Figure 2 only shows one cut-off, we apply the procedure separately for moderate and severe levels of IDA (whereby we avoid double counting) and for the three dietary regions in India. The calculated current distribution functions of adult equivalent iron intakes are shown in Figure 3 for the dietary regions.

Reduced IDA prevalence with iron biofortification of rice and wheat are shown in Table 2. 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 Figure 4. 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%.[15] 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, which can still be influenced through appropriate R&D policies. Rice biofortification alone produces higher benefits than wheat biofortification, mainly due to (i) the lower iron bioavailability in wheat eating populations and consequently higher cut-off levels to avoid IDA and (ii) somewhat higher prevalence rates of IDA in this region, which makes the deficiency more severe and more difficult to overcome.

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[14] Zimmermann and Qaim (2004) use recommended dietary allowances (RDAs). '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, 2000a: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, 2000a: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 *et al*., 2002:785; also c.f. Murphy *et al*., 2002:270-271 and IOM 2000a, esp. Fig. 4-8).

[15] See the appendix for a comparison with the results of an analysis based on the 'dose-response'.
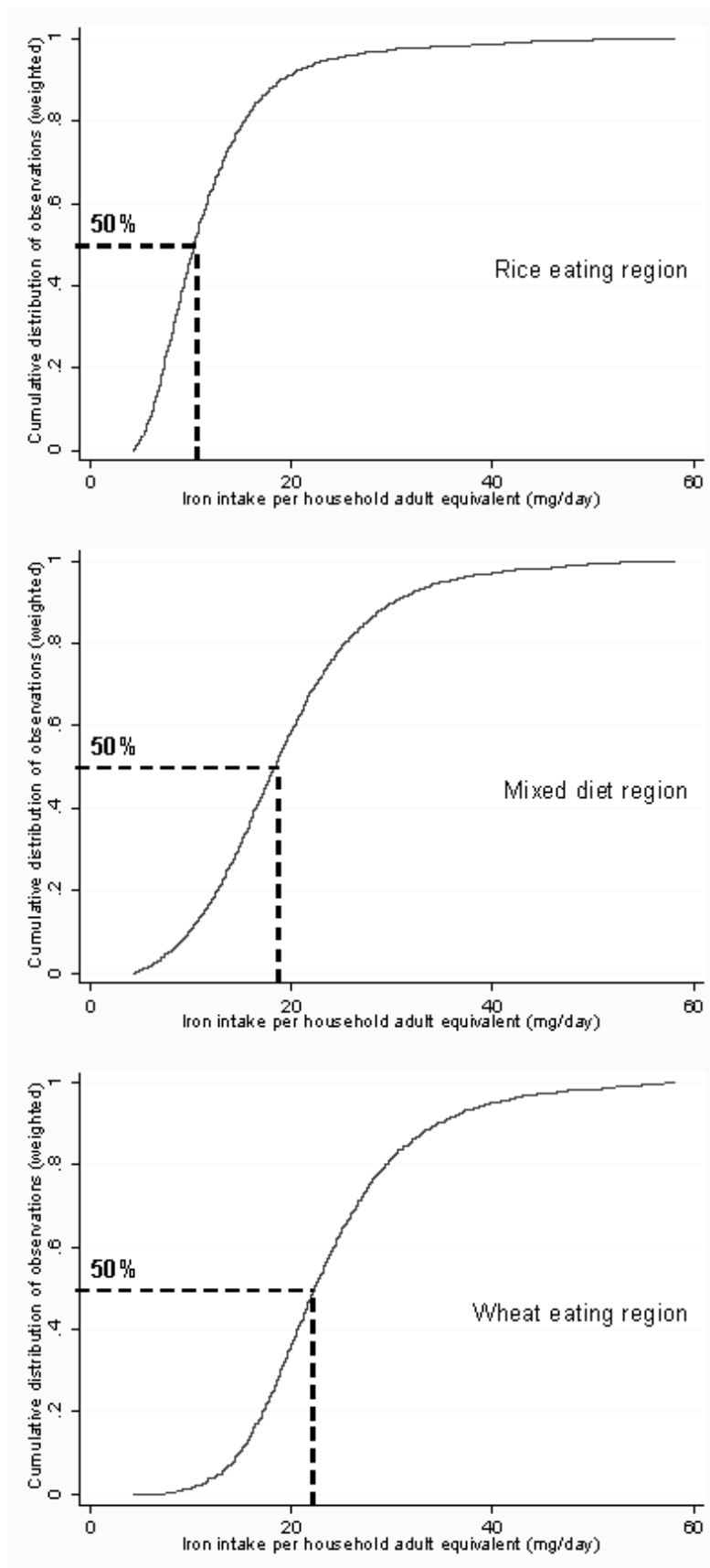
Figure 3. Cumulative distribution functions of iron intakes by dietary region

Note: We carried out separate analyses for each region, because the median iron intake as well as the bioavailability of iron differ between the dietary regions.
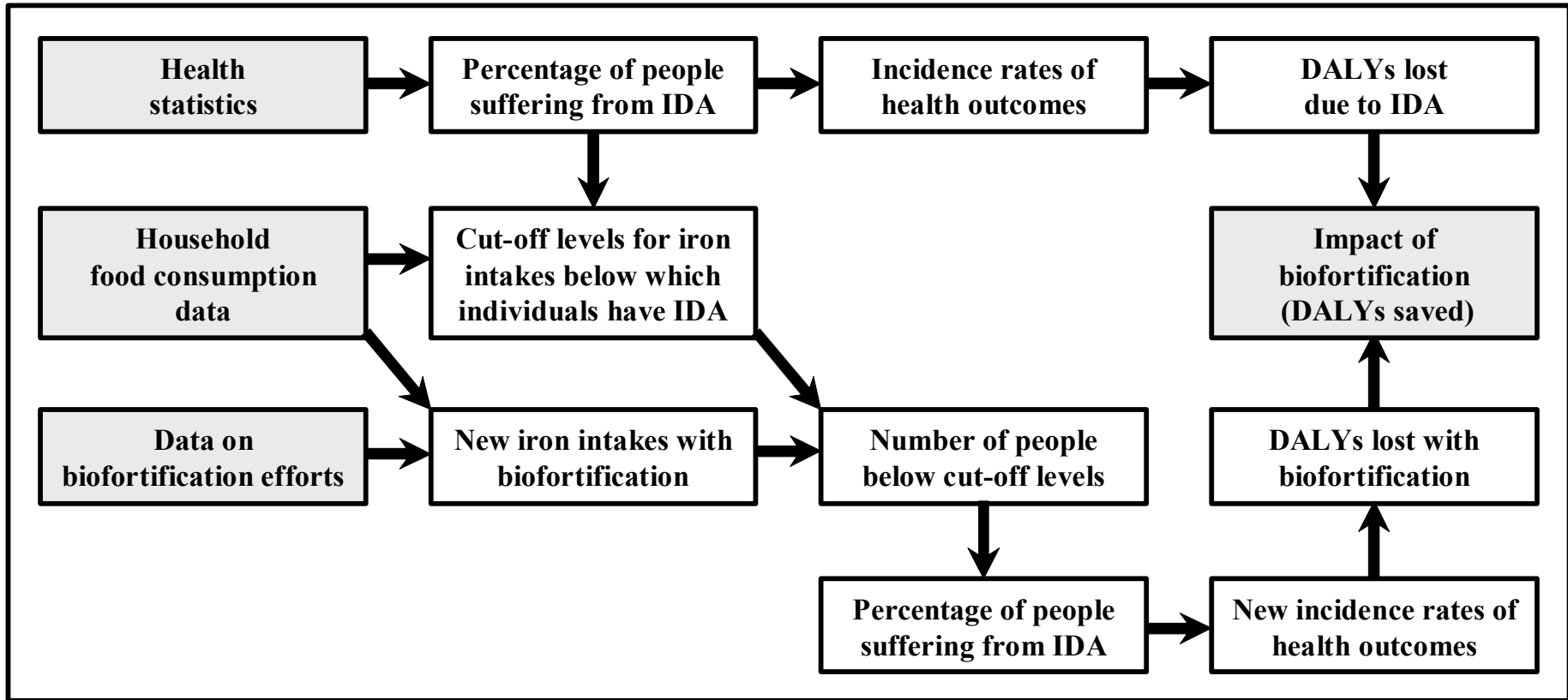
Figure 4. Layout and rationale of method to calculate the impact of biofortification

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: 4.0 m)						
DALYs lost even 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: 1.1 m)						
DALYs lost even 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: 1.3 m)						
DALYs lost even 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: 1.6 m)						
DALYs lost even 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%

5   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 and CIMMYT. Because iron content is only 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 for the pessimistic and optimistic scenarios. 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.

Table 5. R&D costs and time structure for iron biofortification

Biofortified crop	Rice only		Wheat only	
Scenario	Pessim.	Optimist.	Pessim.	Optimist.
Share of int. 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

Sources: CIAT/IFPRI (2004) and information of the project leaders at IRRI and CIMMYT.

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, 2004b). 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). IRRI and CIMMYT are already introducing the iron trait into some popular varieties grown in India. 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. Besides the maintenance breeding, biofortification is not expected to involve major recurrent

costs, which is one of its advantages vis-à-vis industrial fortification or pharmaceutical sup-plementation.[16]

Once biofortified crops are released in the country, over time, with more iron-rich rice and wheat varieties becoming available, adoption rates will increase. In calculating health bene-fits, we assume a linear diffusion curve, until the coverage rates mentioned in the previous section have been reached after 20 years. Dividing the discounted monetary costs by the dis-counted number of DALYs saved yields an average cost per DALY saved, which we take as our measure of cost-effectiveness. The results are summarised in Table 6.

Table 6. Cost-effectiveness and cost-benefit analysis of iron biofortification

Biofortified crop	Rice & wheat		Rice only		Wheat only	
Scenario	Pessim.	Optim.	Pessim.	Optim.	Pessim.	Optim.
Cost-effectiveness (US$ per DALY saved)	5.39	0.46	3.96	0.30	8.71	0.63
CBA with a value of US$ 500 per DALY						
Internal rate of return (%)	50	141	54	156	41	110
Benefit-cost ratio	93	1090	126	1650	57	793
CBA with a value of US$ 1000 per DALY						
Internal rate of return (%)	61	168	65	185	50	129
Benefit-cost ratio	186	2180	252	3300	115	1587

Depending on the assumptions made, the cost per DALY saved ranges between 30 cents and 8.70 dollars. Cost-effectiveness is higher for rice biofortification alone than it is for com-bined rice and wheat biofortification, partly because of the higher consumption of rice relative to wheat. Furthermore, regional differences also play an important role in this respect: wheat biofortification will have little impact on IDA in rice eating regions. To put the cost-effective-ness results into a broader context of health policies, the World Bank (1993) describes costs per DALY saved of US $ 1-3 as 'most cost-effective' and costs less than US$ 25 as 'remarka-bly low'. Interventions that cost between US$ 50-150 per DALY saved are classified as 'highly cost-effective'. Hence, our results suggest that iron biofortification of rice and wheat are very cost-effective interventions. Moreover, biofortification appears to be more cost-

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[16] If India's iron supplementation programme 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 U. Kapil, 2004, personal communication). Yet, simply comparing costs provides little information on the desirability of a pro-gramme as long as the benefits differ. For example, a well functioning supplementation programme may provide higher doses of iron and, hence, achieve a bigger health impact (among individuals that are severely deficient). At the same time, such a programme can be expected to be more expensive. Therefore, costs and effects need to be made comparable in a cost-effectiveness analysis or in a cost-benefit analysis.

effective than iron supplementation programmes (US$ 12.8 per DALY saved) and still more cost-effective than iron fortification of food (US$ 4.4 per DALY saved) (Gillespie, 1998).[17]

6 Cost-Benefit Analysis

As we had discussed in section 2, DALYs have the advantage that they capture the disease burden directly and can be used in cost-effectiveness analyses for making meaningful decisions about the implementation of alternative interventions that impact on health. However, there are other (agricultural) R&D projects that are not or cannot be quantified using DALYs. To be able to compare across such projects, cost-benefit analysis (CBA) has to be used, which necessitates the translation of health benefits (DALYs saved) into monetary benefits.

By attributing a dollar value for each DALY saved we do not pretend to quantify the intrinsic value of human life as such or to reflect its value to the individual concerned. Such a valuation of DALYs (or of the related 'quality-adjusted life years') to build a bridge between cost-effectiveness analyses and CBAs is – rightly – disputed on more general theoretical grounds (Dolan and Edlin, 2002; Krupnick, 2004). Nevertheless, some sort of valuation to answer decision problems in the real world is deemed necessary (Buxton, 2005). Therefore, in the present CBA we do not undertake to capture the full value individuals or society may attach to a DALY; we only approximate the average tangible economic loss that can be associated with the loss of a DALY in the short run. Obviously, such an approximation can only indicate the very lowest bound of the monetary value of a DALY, and may provide an idea of the orders of magnitude involved: if the results of such an analysis should indicate that biofortification is more profitable than other interventions, one can safely claim that using more comprehensive DALY values does not change the ordinal ranking of the profitability of the different interventions.

Other DALYs literature proffers advice on possible values to use for our purpose. Van Houtven et al (2006) use meta regression analysis to link WTP to health status measures similar to those used here. Other authors use average annual per capita incomes to value each DALY (Zimmermann and Qaim, 2004) and others use standardised values of US$ 500 or US$ 1000 in the context of developing countries (Collier and Hoeffler 2004; Rijsberman 2004). Using standard values facilitates comparisons across different countries and interventions, which is our goal. Therefore, we use both US$ 500 and US$ 1000 in the CBA of iron biofortification. (India's per capita income in 2004 was US$ 620 (World Bank, 2005).)[18] The

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[17] In terms of 2004 dollars, these DALY costs are US$ 1.5-4.3, US$ 36, US$ 72-217 (from 1990 dollars), and US$ 5.1-14.8 (from 1998 dollars), respectively (inflation calculator of the US Bureau of Labor Statistics, http://data.bls.gov/cgi-bin/cpicalc.pl).

[18] Other possibilities to value one DALY are to use triple the per capita income (WHO 2001b), per capita income at purchasing power parity (PPP) or to derive a value from estimates of the 'value of a statistical life' (VSL), the latter of which could be seen as an attempt to capture more than the direct economic dimension of a DALY. India's per capita income at PPP was US$ 2,684 in current prices in 2000 (Heston *et al.*, 2002). Based on the VSL estimates of Miller (2000), a DALY value of about US$ 2,500 could be derived. However, using these

results are shown in the lower part of Table 6 as internal rates of return (IRRs) and benefit-cost ratios (BCRs).

Even these partial returns on R&D investments are sizeable, with IRRs being higher than for many other agricultural research projects (c.f. Alston *et al.*, 2000). But how do the measures compare with non-agricultural micronutrient interventions? In an early study capturing different developing countries, Levin (1986) calculated BCRs in the range of 5-79 for industrial, commercial iron fortification and of 1.6-59 for pharmaceutical supplementation. In a more recent overview, Behrman *et al.* (2004) gave BCRs of 176-200 for iron fortification and of 6.1-14 for supplementation. Horton and Ross (2003) find BCRs of 6-36 for iron fortification programmes in 10 developing countries and Horton (1999) gave values of 3.6-10.3 for iron supplementation in different Asian countries. Yet, these studies are also partial in the sense that they only look at tangible economic benefits in terms of increased worker productivity but fail to capture the benefits of the interventions that accrue outside the labour market. On the other hand, while for instance impaired physical activity may be measured either via the loss in productivity it causes or via the corresponding loss in DALYs, in both cases the health care costs that are caused by IDA are not take into account.[19]

Apart from using the direct short-term economic value of a DALY to carry out CBAs, this value can also be used to evaluate the direct overall economic loss that is caused by IDA in India each year. In this context using the average Indian per capita income (US$ 620 in 2004, World Bank, 2005) instead of the standardised values that are used to compare interventions across different countries is more pertinent. The resulting direct annual economic loss due to IDA amounts to US$ 2.5 billion. In relation to India's gross national income of US$ 674.6 billion in 2004 (World Bank 2005), this amounts to an annual loss of 0.37%. But again, this loss can only indicate a lowest bound, even for the economic loss, because it represents a static analysis. As we have highlighted above, malnutrition and poor health may be significant determinants for economic growth. Hence, reducing the prevalence of IDA in India could trigger important dynamic interactions between better health and higher economic growth, thus leading to substantially higher overall development achievements.

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higher DALY values would boost the monetary benefits of biofortification considerably and, hence, its profitability. As our intention is to establish a lower bound of the profitability of biofortification, we do not report the corresponding results here. Detailed results can be made available upon request.

[19] In this case the implicit assumption is that the health care costs (for IDA these are mostly the costs of supplementation and fortification) are exactly compensated by the health/productivity gains they create. Yet, the efficacy of the Indian iron supplementation programme is generally considered to be low (Kapil, 2003; Vijaya-raghavan, 2002), i.e. it imposes costs but generates only few benefits. By neglecting these costs we therefore underestimate the full monetary costs of IDA and, hence, our results are very conservative. However, other studies on the economics of iron deficiency do not take health care costs into account, either (c.f. footnote 7).

7 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, a gap we attempt to bridge in this paper. While innovations in agriculture usually result in yield increases or input savings, in the case of biofortification the benefit is improved health. Therefore, to assess this impact and the cost-effectiveness of biofortification, we refined the method of disability-adjusted life years (DALYs) to quantify potential health benefits of iron-rich rice and wheat. The DALYs approach has hardly been used in agricultural economics before, but it is a suitable tool for analysing the health dimensions of food security more explicitly, and has the advantage of circumventing the contentious issue of valuation of health benefits. Further contributions of this paper have been to use a large food consumption data set and a cumulative distribution function of iron intakes to explicitly tie food consumption with adverse functional outcomes and to embed this within the DALYs framework. We also discussed the limitations of relying on the financial capacities of the individuals reached to evaluate health interventions, as is done in cost-of-illness or willingness-to-pay analyses. We showed that the DALYs approach captures more comprehensively the impact of diseases on the ability of people to realise their physical and mental potential – which in turn may feed back into their earning capabilities and influence overall economic development. Besides these methodological innovations and discussions, our empirical findings can help better understand the potential effectiveness and efficiency of iron biofortification compared with other micronutrient interventions.

We calculated that 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. Depending on the economic value attributed per DALY saved, a conservative approximation of the rate of return on R&D investments ranges between 50 and 168%. Because some impact parameters are hard to anticipate ex-ante, these results should be treated as preliminary. The differences between the two scenarios analysed 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. Other assumptions whose robustness with regard to the final results could, so far, only be ascertained through sensitivity analysis are the discount rate of the Indian society for future health gains and, more crucially, the (economic) value that should be attributed to a DALY. Another issue that could only be highlighted in this article is the potential negative impact of ID – and hence the concomitant positive impact of iron biofortification – on economic growth.

Nevertheless, in this article we could put forward a consistent and comprehensive framework for the economic analysis of malnutrition and (agricultural) nutrition interventions at the micro-level. Our results demonstrate that 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 in other organizations is being supported under the Grand Challenges in Global Health Initiative. Thus, developing countries will have better access to micronutrient-rich lines in the future, 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.

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Appendix: A Comparison of Methods

Given that there already has been another DALY-based assessment of a biofortified crop that makes do with considerably lower data requirements, namely simple national average intakes of the micronutrient in question and a set of DRIs, rather than a nationally representative food consumption data set (Zimmermann and Qaim 2004), one interesting question is whether the more complex and time and resource intensive methodology we propose here is justified. In the main text of our paper (in the section 'Potential Benefits of Iron Biofortification' under the heading 'Health Improvement' on p. 14), we already discussed the theoretical shortcomings of an approach that uses average intakes and externally set DRIs. But to illustrate these theoretical weaknesses we have also calculated the potential impact of iron-rich rice and wheat on the burden of IDA in India based on the approach used by Zimmermann and Qaim (2004). We used simple national average intakes for adult women, adult men, girls aged 16-18 years, boys aged 16-18 years, girls aged 13-15 years, boys aged 13-15 years, girls aged 10-12 years, boys aged 10-12 years, children aged 7-9 years, children aged 4-6 years, children aged 1-3 years and infants to determine the efficacy of iron-rich rice and wheat in closing the intake gap between average current iron intakes (*CI*) and several DRIs (Table 7). The very different results indicate that the bias due to comparing average intakes with DRIs may be important, indeed.

The very different result may be explained by way of example: the average current iron intake (*CI*) of target group i be 10 mg/d. With iron biofortification of rice and wheat, the average iron intake (*BI*) of target group i be 15 mg/d. If the DRI (*RDA* or *EAR*) is set at 25 mg/d, then the original shortfall is 15 mg/d, which is closed by one third through biofortification. If the DRI is set at 16 mg/d, then the original shortfall is only 6 mg/d, but this shortfall is almost eliminated through biofortification (i.e. the effectiveness of biofortification is very high). If the DRI is set at 12 mg/d, then the original shortfall is 2 mg/d, and this shortfall is completely closed through biofortification (i.e. based on the average intake data biofortification can be expected to eliminate IDA completely). Finally, if the DRI is set at only 10 mg/d, then – to judge from the average intake data – there was no shortfall and biofortification cannot improve this situation, i.e. its effectiveness is zero. However, if the epidemiological data indicates that IDA is prevalent, the question is what happened to the iron deficient individuals if not shortfall can be discerned? The obvious answer is that average iron intake data does not provide any information on the lower end of the intake distribution in the respective target group (where the deficient individuals are located) and can, therefore, conceal the problem of IDA in such kind of analyses. This issue is illustrated in Figure 5: if the intake distribution is

Table 7. Comparison of the results obtained through our methodology with possible results of the previous, more limited approach

Biofortified crop	Rice & wheat		Rice only		Wheat only	
Scenario	Pessimistic	Optimistic	Pessimistic	Optimistic	Pessimistic	Optimistic
DALYs lost in the *status quo* in all of India	4.0 m	4.0 m	4.0 m	4.0 m	4.0 m	4.0 m
Disaggregated analysis based on the cumulative distribution function of iron intakes						
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%
Analysis of national mean iron intakes based on the dose-response function and the RDAs of Gopalan et al. (1989)						
DALYs saved through biofortification	0.5 m	1.7 m	0.3 m	0.5 m	0.3	1.3
Decrease relative to *status quo*	-13%	-42%	-7%	-14%	-7%	-32%
Analysis of national mean iron intakes based on the dose-response function and 70% of the RDAs of Gopalan et al. (1989)[a]						
DALYs saved through biofortification	1.9 m	2.6 m	1.0 m	1.9 m	1.1 m	3.0 m
Decrease relative to *status quo*	-47%	-65%	-26%	-47%	-27%	-74%
Analysis of national mean iron intakes based on the dose-response function and RDAs for vegetarians of IOM (2000b)[b]						
DALYs saved through biofortification	0.6 m	1.7 m	0.3 m	0.6 m	0.3 m	1.3 m
Decrease relative to *status quo*	-15%	-42%	-8%	-16%	-9%	-33%
Analysis of national mean iron intakes based on the dose-response function and the RDAs of IOM (2000b)[c]						
DALYs saved through biofortification	0.4 m	0.8 m	0.2 m	0.4 m	0.2 m	0.7 m
Decrease relative to *status quo*	-9%	-19%	-5%	-10%	-5%	-18%

Analysis of national mean iron intakes based on the dose-response function and the EARs for vegetarians of IOM (2000b)

DALYs saved through biofortification	0.1 m	0.1 m	0.1 m	0.1 m	0.1 m	0.2 m
Decrease relative to *status quo*	-4%	-2%	-1%	-2%	-1%	-4%

Analysis of national mean iron intakes based on the dose-response function and the EARs of IOM (2000b)[c]

DALYs saved through biofortification	0.0m	0.1 m	0.0m	0.0 m	0.0m	0.1 m
Decrease relative to *status quo*	-1%	-3%	-1%	-1%	-1%	-3%

Notes: [a]70% of the RDA value corresponds approximately to the respective EAR value, which is not given in Gopalan *et al*. (1989); in footnote 14 we have argued that RDAs are not a useful reference standard for assessing population nutrition status but that EARs should be used. [c]Disregarding the doubtfulness of using RDAs in the first place, even though these results appear to coincide with the results of the analysis that uses the RDAs of Gopalan *et al*. (1989), the underlying RDA values differ: e.g. the IOM-RDA for vegetarian adult men is 14.4 mg/day, while Gopalan's corresponding RDA is 28 mg/day. [c]The IOM determines the DRIs for the population of the USA and Canada, i.e. for people who consume a mixed diet that contains in particular a lot of meat, which is an important source of heme iron and also improves the absorption of non-heme iron from other food source. Hence it could be argued that using such DRIs for the Indian population is misleading as this population eats a predominantly vegetarian and cereal-based diet with a low bioavailability of the dietary iron. (Yet, as Figure 3 illustrates, diets within India differ as well considerably and, hence, using one DRI for all of India may be just as misleading and produce biased results.)
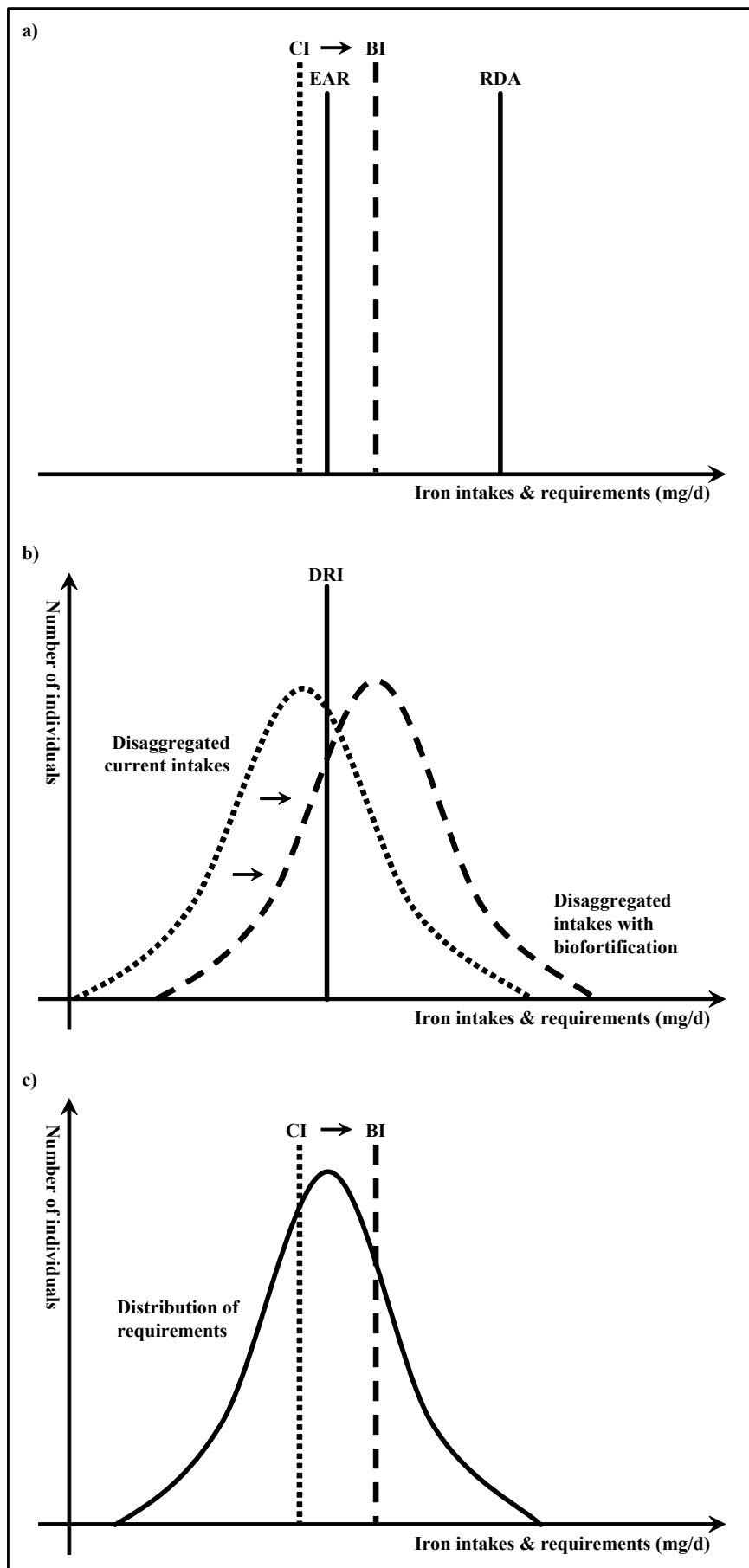
Figure 5. Illustration of iron intake distributions, their mean, the iron requirement distribution and the related DRIs.

disregarded, as in panel a), the result of comparing average intakes to any kind of DRI depends entirely on the choice of the DRI and even a minor change in average intakes can seemingly eliminate the shortfall in iron intakes.[20] Given the difficulty of finding the correct level for the DRI and given the little information that is conveyed in average intakes, our method is clearly more reliable. Because (i) we use a comprehensive data set to determine the full distribution curve of iron intakes for each target group, (ii) we match the cumulative distribution curve with the actual prevalence rate for each target group to derive a suitable threshold to determine insufficient iron intakes (i.e. we internally derive an appropriate and consistent 'DRI' for each target group) (c.f. Figure 2), and (iii) we take account of dietary heterogeneity and the related difference in the bioavailability of iron through carrying out steps (i) and (ii) for each dietary region separately (c.f. Figure 3).

Still, if there is consensus about the correct DRI and if information on the *complete* intake distribution curve is used, an approach based on the dose-response function can nevertheless produce reliable results because the improvement in micronutrient intakes at the lower end of the distribution explicitly enters the calculation (c.f. Figure 5, panel b). However, in this case the dose-response needs to be calculated for each observation, i.e. the analysis invariably becomes more complex, too.[21] In some settings no detailed consumption data may be available, though. To be able to assess the potential impact of biofortification nevertheless, one way to avoid comparing mean intakes with mean requirements (or other DRIs) could be to estimate the distribution of requirements in the target population and adapt the dose-response function accordingly (c.f. footnote 14 and Figure 5, panel c).

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[20] This is spelled out explicitly by Murphy *et al*. (2002:270-271): 'There are several incorrect methods of evaluating the intakes of groups. One is to compare mean intake with the EAR. This approach is incorrect because if mean intake were at the EAR, half of the group would have inadequate intakes. A 50% prevalence of inadequacy is seldom acceptable. Knowing that the mean intake of a group is above (or below) the EAR has no meaningful interpretation. A second incorrect approach is to compare the mean intake of a group with the RDA. Although this seems to be an attractive alternative (especially if the full intake distribution is not known), it is not a very useful approach. Mean intake can equal the RDA and the group often will still have a high prevalence of inadequacy. [...] it is always better to look at the intake distribution, than to examine only the mean intake.'

[21] Yet, even with disaggregate consumption data, using the dose-response approach for analysing the impact of *iron* biofortified crops is not possible because the requirement distribution of this particular micronutrient is not symmetrical and therefore DRIs cannot be used to determine the proportion of iron deficient individuals in a given group (c.f. Barr *et al*., 2002; Murphy *et al*., 2002).

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