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Genetic Engineering for the Poor: Golden Rice and Public Health in India

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Summary. — Vitamin A deficiency (VAD) affects millions of people, causing serious health problems. Golden Rice (GR), which has been genetically engineered to produce β-carotene, is being proposed as a remedy. While this new technology has aroused controversial debates, its actual impact remains unclear. We develop a methodology for *ex ante* evaluation, taking into account health and nutrition details, as well as socioeconomic and policy factors. The framework is used for empirical analyses in India. Given broad public support, GR could more than halve the disease burden of VAD. Juxtaposing health benefits and overall costs suggests that GR could be very cost-effective.

Key words — vitamin A deficiency, biofortification, Golden Rice, disability-adjusted life years, cost-effectiveness, India

1. INTRODUCTION

Vitamin A deficiency (VAD) is a considerable public health problem in many developing countries: it affects 140 million pre-school children and 7 million pregnant women worldwide. Of these, up to 3 million children die every year (UN SCN, 2004). Apart from increasing child mortality, VAD can lead to visual problems, including blindness, and it increases the incidence of measles (Sommer & West, 1996). This affects public health, economic productivity, and individual well-being. Income growth alone is not expected to reduce micronutrient malnutrition in the short to medium term (Haddad, Alderman, Appleton, Song, & Yohannes, 2003). Pharmaceutical supplementation and food fortification with vitamin A (VA) are commonly practiced, but these programs also have their shortcomings: for example, those children that tend to be most at risk of VAD are least likely to receive VA supplements (Adamson, 2004), and extending program coverage is becoming increasingly difficult. Golden Rice (GR), which has been genetically engineered to produce β-carotene, a precursor of VA, has been proposed as another intervention to control VAD (Ye *et al.*, 2000). However, the usefulness of GR is questioned by some, and the technology has become one of the centerpieces in the public

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controversy over genetically engineered crops. Because GR is still at the stage of research and development (R&D) its actual effectiveness remains unknown (Grusak, 2005; Nuffield, 2003). So far, a sound and in-depth scientific analysis of the potential impact has been missing. While partial impact studies show the technology's potential for deficient populations (Dawe, Robertson, & Unnevehr, 2002; Zimmermann & Qaim, 2004), the public debate is dominated by biased assessments of anti-biotechnology groups that are not peer-reviewed and only published on activist websites (Greenpeace, 2005; Shiva, 2000). Most of the conclusions thus derived do not withstand thorough scientific scrutiny, as will be discussed later in this article where appropriate. This is not to say that issues of public interest should be dealt with only at a scientific level, but a profound and objective analysis could still contribute to a rationalization of the debate and help policy makers in their decisions.

We develop a methodology for comprehensive *ex ante* evaluation, which substantially improves upon the previous, more partial impact studies. Dawe *et al*. (2002) focused on the potential effects of GR on β-carotene intakes, but without considering actual health impacts. Zimmermann and Qaim (2004) considered health aspects, but only at a highly aggregate level and without taking into account important nutritional features like dietary heterogeneity across different regions and social groups or the role of reference intakes in dietary assessments. We use a truly interdisciplinary approach, integrating epidemiological and nutrition details, as well as socioeconomic and policy factors. In particular, we determine the current public disease burden of VAD in a country with an important rice-eating population, and simulate to what extent this burden could be reduced through GR. The simulations build on new insights of the technology's efficacy (Paine *et al*., 2005). Finally, we assess the cost-effectiveness of GR more comprehensively than the previous work and compare the results with the cost-effectiveness of alternative VA interventions and other public health programs.

The empirical analysis is carried out for India, where GR lines are currently adjusted to local conditions and are likely to be released in 4–6 years. Of the 140 million pre-school children suffering from VAD world-wide, more than 35 million live in India (UN SCN, 2004). Coverage levels of the existing national VA supplementation program are low (Planning Commission, 2002). Since rice is widely consumed in the country, introducing GR may reduce the prevalence of VAD and free scarce resources in the health sector.

2. METHODOLOGY

Although the extent of VAD in a country is generally captured by prevalence rates, merely counting the number of people below a certain threshold for VA sufficiency fails to take account of the problem's depth. Disability-adjusted life years (DALYs) provide a means to measure the total disease burden in one single index. This is done by weighting different health conditions (including premature death) according to their severity and adding up their duration. [1] DALYs were first used in the "World Development Report 1993" (World Bank, 1993) and subsequently elaborated and popularized in "The Global Burden of Disease" report (Murray & Lopez, 1996). In a study on the potential health benefits of GR in the Philippines, DALYs were introduced in an analysis of the benefits of an agricultural technology (Zimmermann & Qaim, 2004). Incorporating more detailed nutrition aspects, we further developed and refined the approach to determine the burden of VAD. Moreover, we improved the methodology to assess the impact of an increased intake of VA on this disease burden through future consumption of GR or other biofortified crops. [2] The present study on the impacts of GR in India is the first empirical application of this methodology. In the following, we provide a more detailed description of the analytical approach and the data used.

VAD itself does not impose a burden on populations that suffer from it; it is the related health outcomes that matter. Proven adverse health outcomes of VAD are night blindness, corneal scars, blindness, measles, and increased mortality among children, and night blindness among pregnant and lactating women. [3] Within the DALY formula (Eqn. (1)) disability weights make different health outcomes comparable: a disability weight of zero corresponds to perfect health, and a weight of one corresponds to a health state equal to death. The other important component of the DALY formula is the inclusion of a time dimension: the full duration of a health outcome is counted in years (or fractions thereof) at the onset of the condition. The duration of permanent diseases is determined by using the average remaining life expectancy at the year of onset; future life years are discounted at a rate of 3% (Stein *et al.*, 2005; Tan-Torres Edejer *et al.*, 2003). Hence, what DALYs measure in our context are healthy life years that are lost due to VAD each year, that is, the disease burden is counted in terms of "DALYs lost":

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

where T_j is the total number of people in target group j, M_j is the mortality rate associated with the deficiency in target group j, L_j is the average remaining life expectancy for target group j, I_{ij} is the incidence rate of disease i in target group j, [4] D_{ij} is the disability weight for disease i in target group j, d_{ij} is the duration of the disease i in target group j (for permanent diseases d_{ij} equals the average remaining life expectancy L_j), r is the discount rate for future life years.

The size of the target groups (children $\leqslant$ 5 years, pregnant women, and lactating women) is based on census data from India (Registrar General, 1991 & 2001) and on the total fertility rate (IIPS, 2000); under five mortality (U5M) rates are taken from UNICEF (2003); incidence rates of night blindness, corneal scars, and blindness are derived from Toteja and Singh (2004); for measles a higher incidence rate is assumed than the one that is given in the official data of the Central Bureau of Health Intelligence (CBHI), because for some states in India no data are available and there is substantial under-reporting. As VAD is not necessarily the only cause for these health outcomes, we attribute appropriate shares of the total incidence of each outcome to VAD (cf. Stein *et al.*, 2005). [5] To determine the average remaining life expectancy and the duration of permanent health outcomes, we use standard life tables for India (WHO, 2001a). The main data used for the calculations are shown in Table 1.

We calculate the current burden of VAD in India—that is, without GR—based on these parameters. To determine the potential impact of GR, we additionally simulate a situation in which GR is consumed: with GR, the intake of β-carotene will be higher than in the current situation in which "normal" rice is consumed. Higher β-carotene intake translates into higher VA intake, which reduces VAD and related health outcomes. This reduction is picked up by lower values for M_j and I_{ij} in Eqn. (1), which also results in a lower number of DALYs lost due to VAD. The difference between the current burden of VAD and the burden in a situation in which GR is consumed is the impact of GR. In the following, we further elaborate on the individual steps.

We use detailed consumption data of a nationally representative household survey in India (NSSO, 2000), which comprises 120,000 households and registered the consumption of about 140 different food items. Based on this consumption data and food composition tables (Erhardt, 2005; Gopalan, Rama Sastri, & Balasubramanian, 1989; USDA, 2004), we calculate the VA intake of each household expressed in micrograms (μg). [6] We then regress variables for the households' composition (age and gender) on VA intakes and use the estimated

Table 1. *Severity, duration, and incidence rates of health outcomes related to VAD*

	Disability weight	Duration (years)	Incidence rate (%)	Attributable incidence (%)
Children ⩽5 years				
Night blindness	0.05	1.00	1.03	100
Corneal scars	0.20	64.40	0.02	10
Blindness	0.50	64.40	0.02	10
Measles (simple)	0.35	0.03	2.70	10
Measles (complications)	0.70	0.06	2.70	10
Under five mortality	(1.00)	64.40	9.30	3
Pregnant women				
Night blindness	0.10	0.42	6.62	100
Lactating women				
Night blindness	0.10	0.50	5.52	100

Note: Data sources are explained in the text. Further details can be found in Stein *et al.* (2005).

coefficients to derive adult equivalent weights. These weights allow us to impute individual VA intakes from overall household consumption. This way we also take into account that children eat less rice and other foodstuffs than grown-ups, which is important for the impact analysis. If current VA intake for an individual, VAI^{old}, is lower than the estimated average requirement (EAR) for the particular target group, [7] there is an "intake gap," that is, the individual can be expected to suffer from VAD. The bigger the intake gap, the more severe the deficiency, and the more likely adverse health outcomes will occur.

In a further step, we replace the food composition value of "normal" rice for β-carotene (0 μg/g) with the β-carotene content in GR (for a certain share of overall rice consumption, cf. Table 2) and derive new VA intakes with GR (VAI^{new}). [8] In this situation, VA intakes are higher than before, so GR helps reduce the intake gap. The health response to such an intake improvement is not linear: the more deficient an individual, the more pronounced the health response of a given improvement in VA (Figure 1). This mechanism is sometimes ignored by the critics of GR, who overlook that all individuals already consume a certain amount of VA, even if it is not enough to achieve full sufficiency. Therefore, they (implicitly) postulate that GR can only be considered effective if its daily consumption supplies enough VA to fulfill 100% of VA requirements. Based on these premises, and using very high (but unreferenced) VA requirements, they suggest—for a *hypothetical* individual—that impossible amounts of GR would need to be consumed (Greenpeace, 2005; Shiva, 2000). Our approach takes better account of the *actual* nutrition-health linkages by following Zimmermann and Qaim (2004) and Stein *et al.* (2005) when calculating the efficacy (E) of the above-mentioned "dose–response" at the individual level according to the following formula:

$$E = \frac{\ln\left(\frac{VAI^{new}}{VAI^{old}}\right) - \left(\frac{VAI^{new} - VAI^{old}}{EAR}\right)}{\ln\left(\frac{EAR}{VAI^{old}}\right) - \left(\frac{EAR - VAI^{old}}{EAR}\right)}. \quad (2)$$

Zimmermann and Qaim applied this dose–response to average national VA consumption figures. Yet, using average intakes to assess the nutrient adequacy of group diets can be misleading, because the prevalence of inadequacy depends on the shape and variation of the intake distribution (Murphy & Poos, 2002). Therefore, we calculate E for each individual in our data set before producing a

Table 2. *Assumptions used to simulate two scenarios in which GR is consumed in India*

Scenario	Low impact	High impact
β-Carotene content in GR (μg/g)	14	31
Post-harvest loss of β-carotene (%)	80	35
Conversion of the β-carotene in GR into VA	6:1	3:1
Coverage rate of GR 15 years after release (%)		
in government shops	20	100
in school meals	20	100
on the free market	14.3	50
in rice products	10	50

Note: Data sources are explained in the text.

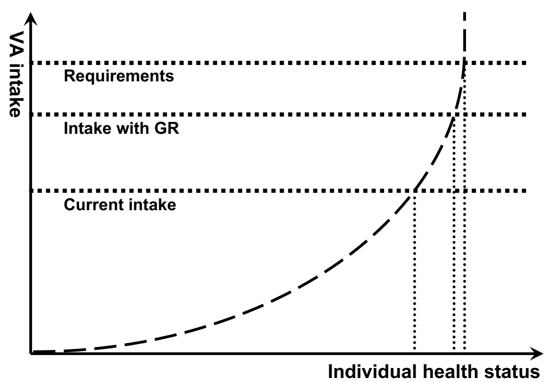

Figure 1. *Illustrative dose–response curve. Source: Based on Zimmermann and Qaim (2004) and Stein et al. (2005).*

weighted average efficacy ratio for the different target groups. As these efficacy ratios reflect the health response due to a change in VA intakes, we can apply them to the current incidence rates of the VAD-related health outcomes, in order to derive a new set of incidence and mortality rates. These lower rates are used to calculate the burden of VAD with GR. Subtracting this reduced burden from the one in the *status quo* results in the number of "DALYs saved" through GR, which is our measure of the technology's impact. Finally, we consider the cost of developing and disseminating GR that is attributable to India, to calculate the cost per DALY saved as a cost-effectiveness measure.

3. SCENARIOS AND ASSUMPTIONS

To take account of uncertainty in this *ex ante* analysis, we simulate a low impact scenario with rather pessimistic assumptions, and a high impact scenario with more optimistic assumptions. Both scenarios are projected over a period of 30 years. Our low impact scenario assumes that GR will experience only limited scientific success and weak political support. Our high impact scenario, in contrast, reflects what the scientists involved deem possible, and what broad political support could accomplish. The underlying assumptions are displayed in Table 2 and explained in the following text.

The β-carotene content in GR is based on the average and maximum levels that could be realized so far (Paine *et al.*, 2005). The expected losses of β-carotene due to storage and cooking are based on estimates by Barry (2005), Dubock (2005), Beyer (2005), and Bouis (2005). Even though for β-carotene in a mixed diet a conversion rate into VA of 12:1 is used (IOM, 2002), better rates for GR are justified due to its simple food matrix, as discussed by Zimmermann and Qaim (2004), and as reconfirmed by Russell (2006), who has been carrying out the first feeding trials of GR with humans. Therefore, we use the rates of 6:1 and 3:1 in our low and high impact scenarios, respectively.

It is assumed that the "golden" trait will be incorporated into at least four new open-pollinated rice varieties whose agronomic traits are superior to current popular varieties, so rejection of these "golden" varieties for agronomic reasons is not expected. GR varieties are developed jointly by the private and public sector and, in the framework of a humanitarian mandate, they will be handed over to small-scale farmers who can reproduce the seeds themselves at no extra cost (Paine *et al.*, 2005; Potrykus, 2001).[9] Furthermore, because it is assumed that the government supports the dissemination and promotion of GR by distributing it through the systems that are in place to ensure food security, like ration shops and school feeding, public authorities will generate demand for GR, thus creating a market and potential outlet for the GR that is grown by early adopters among the farmers.

The situation on the side of the consumers is different, though. While the government can influence what is sold in its ration shops that cater for the poor and what is distributed in school meals,[10] the free market follows actual consumer demand. For the free market, we assume that—15 years after release of the first varieties—in the low impact scenario people eat GR only on one day per week, while in the high impact scenario they eat GR every other day. This range is meant less to predict actual future consumption patterns but to reflect possible consequences of policy decisions (that have not yet been made) and of future social marketing activities, as explained below.

The cost estimates for GR, which explicitly include costs for social marketing activities, are shown in Table 3. The base year for our analysis is 2001, when the development of GR as a crop started; all costs were discounted to this year at a common social discount rate of 3% (Tan-Torres Edejer *et al.*, 2005; World Bank, 1993). In the low impact scenario, we increased costs that occurred before 2005 by 10% to account for possible under-reporting, while we increased the estimates of the more uncertain future costs by 25%. In the high impact scenario, we only increased the estimates of the future costs by 10%. The international R&D costs are based on costs reported by Mayer (2005), Dubock (2005), and Barry (2005) for the University of Freiburg, Syngenta, and IRRI, respectively. To attribute a share of these overall costs to India, in the low impact scenario we used India's share of 70.5% in the total rice production of India, Bangladesh, and the Philippines, as these are the core beneficiary countries suggested by the Golden Rice Humanitarian Board. In the high impact scenario, we included China as another potential beneficiary country, which resulted in a cost share of 34.2% for India (production data from FAO, 2004). The R&D costs within India are

Table 3. *Time frame and cost estimates for R&D and dissemination of GR in India*

	Low impact scenario		High impact scenario	
	Years	Undiscounted cost (US$)	Years	Undiscounted cost (US$)
International R&D	2001–07	7,462,000	2001–07	3,262,000
R&D within India	2002–11	1,158,000	2002–09	780,000
Regulatory process	2003–12	2,515,000	2003–10	2,213,000
Release of GR	2012–13		2010–11	
Social marketing	2013–15	15,570,000	2011–15	30,710,000
Maintenance breeding	2013–29	2,125,000	2011–29	1,900,000
Net present value of total cost (discounted at 3%)	2001–30	21,384,000	2001–30	27,937,000
Cost annuity	2001–30	713,000	2001–30	931,000

Note: Data sources are explained in the text.

based on the corresponding budgets of the Indian Agricultural Research Institute (IARI), the Directorate for Rice Research, and the Tamil Nadu Agricultural University, as reported by Singh (2005). Costs that need to be incurred for the regulation and control of potential environmental and human health risks are based on estimates by Rao (2005) and include the costs that are expected to arise in the framework of the institutional biosafety committees, the Review Committee on Genetic Manipulation, the Genetic Engineering Approval Committee, and the Seed Act.

The consumer price of GR is expected to be equal to conventional rice, because R&D costs at the international level are borne by donors, and it is assumed that the national costs are borne by the Indian government. Nonetheless, consumer acceptance problems might occur because of the yellow color of the grain. In order to prevent price discounts (which would lower adoption incentives for farmers) and achieve wide-spread consumption, social marketing, and education activities as well as additional extension work will be necessary to promote GR adoption by farmers and acceptance among consumers. At this point, the concrete design of these activities is still somewhat unclear. To get a sense for possible costs, we used expert estimates of the costs for different combinations of awareness programs and campaigns in the framework of India's Integrated Child Development Services (ICDS) centers, including video spots and country-wide campaigns in the electronic media. In the low impact scenario, we projected lower costs for a less intense campaign, while in the high impact scenario, a longer and more intense GR campaign is assumed. The latter would reflect stronger public and policy support, which also

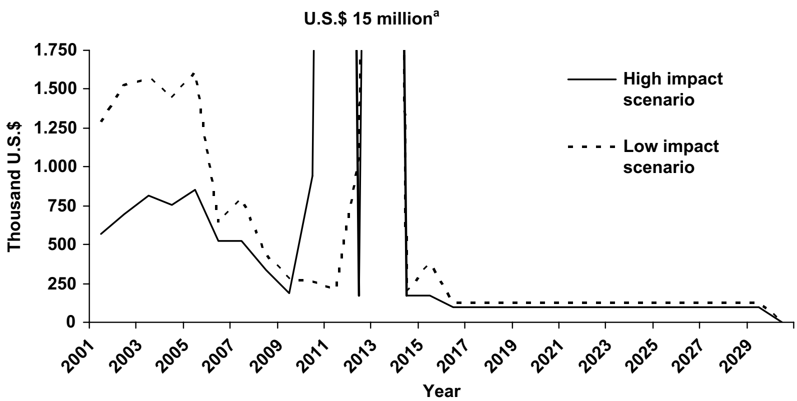

Figure 2. *The structure of the costs of GR in India. Notes:* [a]*Two peaks of US$15 million (for social marketing costs) in the high impact scenario and one in the low impact scenario.*

justifies the assumption of higher coverage rates of GR in the high impact scenario (cf. Table 2). Finally, the costs for maintenance breeding are based on estimates by Barry (2005). The resulting cost structure (Figure 2) confirms the argument that biofortification can be a very sustainable intervention once the initial investments in R&D and variety dissemination are made (cf. Bouis, 2002; Nestel, Bouis, Meenakshi, & Pfeiffer, 2006). These costs also have to be seen in the context of the expenditures that need to be incurred for alternative VA interventions such as the existing VA supplementation program in India: the supplementation costs for only 50% of all pre-school children in India exceed US$100 million and need to be incurred *each year* (Stein, 2006).

Table 4. *The annual burden of VAD in India and the cost-effectiveness of GR*

Scenario	Low impact	High impact
Current burden of VAD		
Number of DALYs lost each year (thousands)	2,328	
Number of lives lost each year (thousands)	71.6	
Potential impact of GR		
Number of DALYs saved each year (thousands)	204	1,382
Reduction of the DALYs burden through GR (%)	8.8	59.4
Number of lives saved each year (thousands)	5.5	39.7
Cost-effectiveness of GR and other VA interventions		
Cost per DALY saved through GR (US$)	19.4	3.1
Cost per life saved through GR (US$)	358	54
World Bank cost-effectiveness standard for DALYs saved (US$)	200	
WHO standard for valuing DALYs (US$)	620–1,860	
Cost per DALY saved through supplementation (US$)	134–599	
Cost per DALY saved through industrial fortification (US$)	84–98	

Source: Stein *et al.* (2006).

4. IMPACT AND COST-EFFECTIVENESS

According to our calculations, the current burden of VAD in India amounts to 2.3 million DALYs lost each year, [11] of which 2.0 million DALYs are lost due to child mortality alone. In terms of incidence numbers, 71,625 preschool children die each year because of VAD, and 3,663 go blind; 2.6 million pregnant and lactating women and 1.6 million children suffer from night blindness, and 0.8 million children succumb to measles. In this context, wide-spread consumption of GR with a high β-carotene content (high impact scenario) can reduce the burden of VAD by 59% and save thousands of lives (Table 4). Less frequent consumption of GR with a lower β-carotene content (low impact scenario) would have a much smaller impact.

Because more disaggregated epidemiological data are not available, we cannot calculate the current burden of VAD separately for different income groups or dietary regions. But the efficacy of GR in closing the VA intake gap can be projected at a disaggregate level, as this is an intermediate and less data intensive step in the calculations (cf. Eqn. (2)). Some further details on these intermediate results might be illustrative for the assessment of differential impacts of GR on different population groups: in the low impact scenario, GR is projected to narrow the VA intake gap by 25% for women and by 11% for children, the difference being mainly due to lower rice quantities consumed by children. The efficacy is higher among the poor households than among the richer ones. For instance, in the low impact scenario, the intake gap for children in the poorest expenditure quintile is reduced by around 13%, while it is reduced by 9% for children in the richest quintile. Hence, GR is a crop that benefits the poor over-proportionally, that is, it is indeed an example of genetic engineering for the poor. In the high impact scenario, the general patterns are the same, but efficacy values are much higher, namely, over 90% for women and over 80% for children. A regional disaggregation reveals that, in the high impact scenario, virtually all individuals (99%) in the predominantly rice-eating states would achieve VA sufficiency status. [12] These results demonstrate the potential of the technology to deliver pro-poor nutrition and health benefits, but the low impact scenario also emphasizes that public support is essential for this potential to materialize. Evidently, for either scenario, delays in bringing GR to farmers can be very costly in terms of DALYs lost that could otherwise be saved.

Our cost-effectiveness analysis indicates that in the high impact scenario, one healthy life year is saved at a cost of US$3.06, while in the low impact scenario, one DALY saved costs US$19.40. However, cost-effectiveness is a relative measure that requires reference values for its assessment. One possible base for comparisons are international standards. In its World Development Report 1993 the World Bank (1993) reported a value of US$150 as a threshold, below which public health interventions can be considered very cost-effective; in current terms this value, which is expressed in 1990 dollars, rises above US$200 (BLS, 2005). The World Health Organisation (WHO, 2001b; http://www.who.int/choice/costs/CER_thresholds/) suggests valuing one DALY at the single to triple *per capita* income to obtain thresholds for very cost-effective and cost-effective public health interventions, respectively. In 2004, the Indian *per capita* income amounted to US$620 (World Bank, 2004). Another possibility for assessing the results is to compare them with the cost-effectiveness of currently implemented alternative interventions. In India, this is VA supplementation, albeit coverage levels of this program are relatively low (Planning Commission, 2002). Also, industrial fortification of foodstuffs with VA is possible and practiced in different other countries. The costs per DALY saved through supplementation and industrial fortification shown in Table 4 are based on a recent study for the WHO region "SEAR-D," which basically comprises South Asia (Tan-Torres Edejer *et al.*, 2005). The costs reported in that study were converted from international dollars into current US$ to make them comparable to our results. [13] The comparison shows that, even under pessimistic assumptions, GR would be more cost-effective than either of these benchmarks (Table 4). These results also indicate that the opportunity costs of the money that is spent on GR would be higher if the money was spent on these alternative interventions: while supplementation and fortification programs can be quite efficient in an urban setting, where there is usually a better infrastructure and where distribution costs can be split among many people, reaching fewer people in more remote rural areas will increase (distribution) costs both in absolute and relative terms, with the mere costs of the supplement or the added VA as such becoming less relevant. Of course, GR also needs to be popularized in these areas, which may be more costly than in urban areas, but it is more sustainable—both in the rural and urban setting—because there are only minor annually recurrent costs, once farmers started cultivating the new varieties (Figure 2).

5. SENSITIVITY ANALYSIS

To test the robustness of our results, we carried out different sensitivity analyses. Figure 3 shows the reduction in the disease burden through GR under varying assumptions. For comparison, the results are displayed next to those of the initial low and high impact scenarios. [14] To examine the influence of variations in effective β-carotene contents and technology coverage rates, we first build on the assumptions of the initial low impact scenario, but increase GR coverage to the levels of the high impact scenario (scenario "a" in Figure 3). Then, we use the assumptions of the high impact scenario, but reduce GR coverage to the

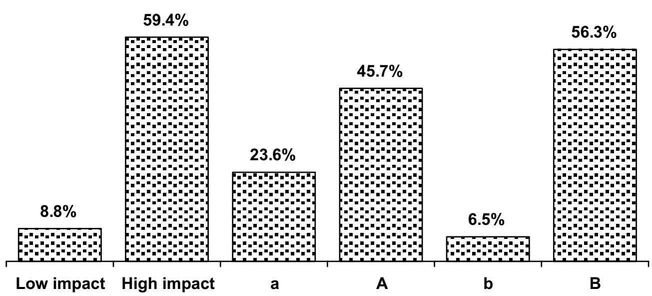

Figure 3. *Reduction of the burden of VAD through GR for different scenarios. Notes: "Low impact" and "high impact" are the initial scenarios; "a" is a scenario where GR has the assumed low level of bioavailable β-carotene, but high coverage rates; "A" assumes an effective high β-carotene content, but low coverage rates; "b" and "B" are the low and high impact scenarios but in the calculation of the dose–response RDAs are used instead of EARs.*

levels of the low impact scenario (scenario "A" in Figure 3). While changing the assumed coverage rates does have a notable effect, scenario "A" demonstrates that the magnitude of the benefits is driven more by effective β-carotene contents. Preferably, high contents and high coverage rates should be sought. Yet, when confronted with a trade-off, these results suggest that priority should be given to achieving higher effective β-carotene contents, which are influenced through actual β-carotene production in the grain, post-harvest losses, and bioavailability. [15]

In our two main scenarios, we use EARs as reference for the VA requirements in the dose–response calculations (cf. Eqn. (2)). EARs are the correct references both for assessing the nutrient intakes of groups and for making quantitative assessments of the adequacy of individuals' usual intakes of a nutrient (Barr, Murphy, & Poos, 2002; IOM, 2002). Another common dietary reference is the RDAs, which add two standard deviations to the EARs. While RDAs are too high to establish sufficiency levels for the majority of the population, we still carried out the calculations based on RDAs for illustrative purposes: impact scenarios "b" and "B" in Figure 3 correspond to the low and high impact scenario, respectively, computed with RDAs instead of EARs. Obviously, when the thresholds to reach sufficiency are pushed up, it takes more to reduce or close the intake gap, so that any intervention that improves intakes becomes relatively less effective. Yet, in this particular case, the choice of the dietary reference only has a minor effect on the overall results.

Apart from these more specific and analytical sensitivity scenarios, we also computed the results of simple percentage variations in the two main areas where we had to rely on assumptions, namely, the R&D and dissemination costs and the projections of how much β-carotene from GR reaches the consumer, determined by β-carotene contents, bioavailability and coverage of GR. Figure 4 shows the cost per DALY saved for variations in these two areas in the low and high impact scenario. The shaded area frames the range of expected outcomes according to the experts' basic assumptions. In the high impact scenario, the changes due to the variations are very small and hardly visible at the chosen scale. In the low impact scenario, the effects are more pronounced. Nevertheless, even for a 50% increase in development and dissemination costs or a 50% lower delivery of β-carotene, GR remains a highly cost-effective VA intervention. Figure 5 shows the impact of GR on the burden of VAD for variations in the amount of bioavailable β-carotene that reaches the consumer. The shaded area again frames the range of expected outcomes. These results show that the main message of the present analysis is quite robust: in the high impact scenario, the burden of VAD in India can be reduced considerably through

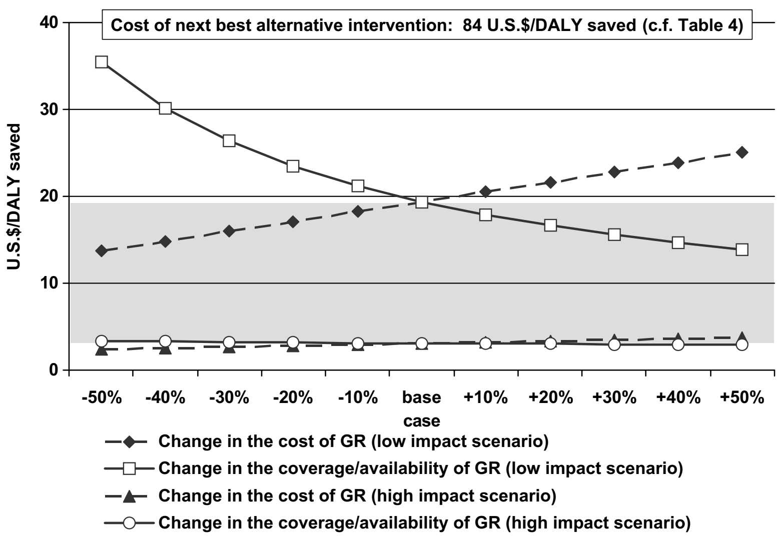

Figure 4. *Costs per DALY saved at given variations in basic assumptions.*

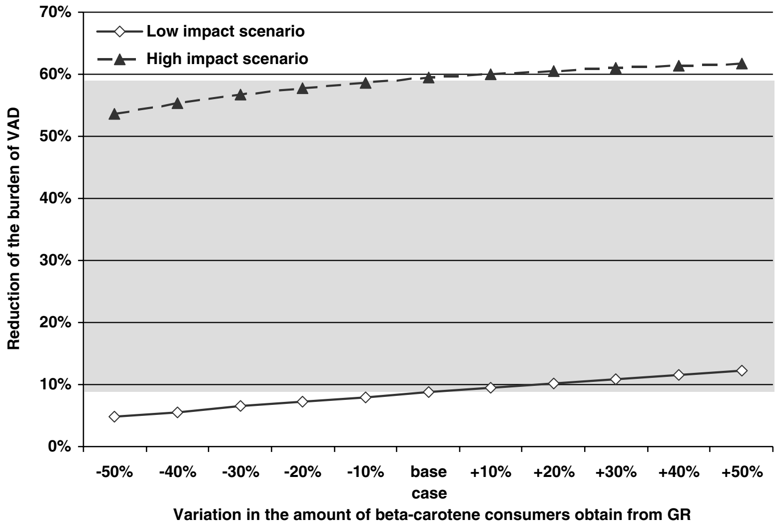

Figure 5. *Reduction of the burden of VAD through GR at given variations in basic assumptions.*

consumption of GR (in the high impact scenario, GR always reduces the burden of VAD at least by half), while in the low impact scenario, the impact on the burden of VAD may be minor—but even then GR remains cost-effective.

A crucial parameter in the cost-effectiveness analysis, and a general point of contention in health economics, is the choice of the appropriate discount rate. Following the literature (e.g., Murray & Lopez, 1996; Tan-Torres Edejer *et al.*, 2005), and to be consistent in our calculations, we discount both future health benefits *and* monetary costs at 3%. However, there is no final agreement on the discounting of future health benefits and lives (cf. Stein *et al.*, 2005). Table 5 shows the cost-effectiveness results of the low and high impact scenarios under varying discount rates. With discounting of monetary costs ($r_{US\$}$) but without discounting of future DALYs (r_{DALYs}), the costs per DALY saved fall, resulting in a higher cost-effectiveness of GR. A rationale for this approach could be that one considers life (and hence DALYs) as an absolute, time-invariant value, which should not be discounted. Refraining from discounting altogether, including for monetary costs, would also lead to lower costs per DALY saved, as compared to the initial scenarios. If, however, the rate for both discounting of DALYs and monetary costs is set at a level higher than 3%, the costs per DALY saved rise, because health gains that occur far in the future weigh less than monetary costs that occur early on in the project. Hence, while not changing the actual impact of GR on the burden of VAD, the valuation of future life years greatly affects the cost-effectiveness of GR. But even with a real discount rate of 10% (which is very high from a social perspective), the cost per DALY saved would still fall into the range of highly cost-effective interventions, as classified by the World Bank and the WHO (cf. Table 4).

Table 5. *The cost-effectiveness of GR with different discount rates*

	Low impact scenario (US$/DALY)	High impact scenario (US$/DALY)
$r_{DALYs} = 3\%$; $r_{US\$} = 3\%$	19.40	3.06
$r_{DALYs} = 0\%$; $r_{US\$} = 3\%$	4.76	0.74
$r_{DALYs} = 0\%$; $r_{US\$} = 0\%$	6.42	1.03
$r_{DALYs} = 5\%$; $r_{US\$} = 5\%$	34.43	5.33
$r_{DALYs} = 10\%$; $r_{US\$} = 10\%$	103.49	14.76

Note: r_{DALYs} denotes the rate at which DALYs saved are discounted; $r_{US\$}$ denotes the rate at which monetary costs are discounted. Further explanations are given in the text.

6. DISCUSSION OF ALTERNATIVES

In the case of India (and elsewhere), current efforts to control VAD concentrate on pharmaceutical supplementation and industrial fortification. Our calculations show that GR could be considerably more cost-effective than these approaches. Yet, there are also other, food-based propositions to fight VAD, like promoting (low yielding) red and black landraces of rice for consumption and further breeding. Such landraces contain up to 0.38 μg/g β-carotene in their unmilled form (Frei & Becker, 2004).[16] In fact, this approach is very similar to the one pursued with GR, only that the use of genetic engineering is avoided. However, promoting these red and black landraces requires consumers not only to accept rice of a different hue but also to change their dietary and food preparation habits, namely, to eat and prepare unmilled rice. Nonetheless, we examine the potential of this proposition in re-running our low and high impact scenarios by using a β-carotene content of 0.38 μg/g, and taking account of lower bioavailability, as the β-carotene is stored in the outer layers of the unmilled rice (bioavailability of 12:1 and 6:1 is assumed). The positive health impact of these landraces would be small: they would only reduce the DALYs burden of VAD by 0.1% and 3.1% in the low and high impact scenario, respectively.

Interestingly, vociferous opponents of GR support the promotion of these landraces, while, at the same time, proclaiming that GR is a failure, because people would need to eat kilograms of it each day to control VAD (Greenpeace, 2005). To achieve the same VA status as with GR, much higher quantities of colored landraces would have to be consumed. Hence, GR is obviously opposed because it is genetically engineered and not because the underlying rationale of increasing the β-carotene content in commonly eaten food is wrong. However, although genetic engineering is required to increase the β-carotene content in rice, it should be noted that breeding nutritionally enhanced crops is generally possible also with conventional techniques, whenever the crop in question shows sufficient genetic variation in micronutrient concentrations; this strategy is followed in the HarvestPlus Challenge Program of the Consultative Group on International Agricultural Research in the crops and for the micronutrients where this is possible (http://www.harvestplus.org/).

Critics of GR often also suggest that the right way to combat VAD would be to increase dietary diversity and rely on food that is already rich in VA or β-carotene, like meat/liver, green leafy vegetables, orange-fleshed roots and tubers, orange fruits, red palm oil, or cod liver oil (Greenpeace, 2005; Shiva, 2000). Indeed, greater dietary diversity and more balanced food consumption is the most sustainable way to achieve long-term nutrition security. However, each suggestion has to be analyzed in the context of the particular situation. For instance, red palm oil or cod liver oil are not typically consumed in India; these oils rather have to be considered medical supplements—and it is the shortcomings of supplementation that GR is expected to partly alleviate. Moreover, red palm oil cannot be consumed straight away, but it has to be refined using special technologies. And, to cover all 140 million children in India aged 6–59 months, about 245,000 tons of red palm oil would be needed. The resulting area requirements for oil palm plantations would compete with other agricultural crops or could potentially threaten biodiversity (cf. Buckland, 2005). Also, while critics find fault with the duration of R&D for GR during which there are no real impacts (Greenpeace, 2005), studies on the use of red palm oil as source of β-carotene in India date as far back as 1936; almost 70 years later the use of red palm oil in India is still not established (Narasinga Rao, 2000).

There are certainly also nutritious foodstuffs, which are consumed in India, and for which further consumption increases would be desirable. However, relying on this avenue alone will not suffice. Meat is rich in VA but it is expensive, and its promotion has certain limits in a society with many vegetarians. Fruits and vegetables can be relatively expensive, too. Also, the β-carotene in some vegetables is of relatively poor bioavailability, and fresh produce is often only seasonally available. Home gardening, which is proposed as a means to ensure the ready availability of fruits and vegetables, might be possible in rural areas, but it comes at the cost of the time needed to tend the garden. A study in Bangladesh demonstrates that, for home gardens to be effective in increasing vegetable consumption, technical assistance is required and households need a regular supply of quality seed and other inputs (Talukder *et al.*, 2000). Human and institutional capacity constraints for management and monitoring further complicate successful implementation, and nutrition education is necessary to achieve behavioral changes. As a measure of success of home gardening programs, the increase in the frequency of vegetable consumption is often used, whereas costs are usually not considered. Given the multiple benefits of frequent vegetable consumption (through improving the overall nutritional status and not just β-carotene intake), it is probably difficult to measure the success of such programs in a more tangible form, but providing some cost estimates—including on the opportunity costs of household labor and volunteer time—would facilitate the relative assessment of different programs. Indeed, neglecting cost aspects is one major weakness of many alternative micronutrient interventions (cf. Ruel, 2001), but effectiveness on its own is a poor policy guide when resources are limited, especially in developing countries (World Bank, 1993).

7. CONCLUSION

We have shown the potential positive impact and cost-effectiveness of GR. Yet, this technology is no panacea in the fight against malnutrition. Neither GR nor any other intervention alone will eliminate VAD. While VA supplementation can address more severe and acute cases of VAD and serve as a preventive measure in the short run, it is costly and less sustainable over longer periods of time. Industrial fortification has its greatest potential in urban areas, whereas poor people in remote rural areas are often not reached due to their low consumption of processed, purchased foodstuffs. Poverty reduction can sustainably reduce not only VAD but also other forms of malnutrition, but this will only happen in the long run. Dietary diversification, breeding food crops for higher micronutrient contents (such as GR), other food-based approaches, and nutrition education are all interventions that have their own strengths and weaknesses. Here we have shown that GR has the potential to reduce the disease burden of VAD in India substantially and at low average costs, even when accounting for sizeable outlays that might be necessary for future social marketing. Therefore, GR promises to be an effective and efficient pro-poor intervention to control VAD. Its inclusion into strategies that aim at the elimination of VAD in rice-eating populations should be considered seriously. Yet the scenario differences also highlight the crucial role of public support. If development and dissemination of the technology are not supported, the impacts will be relatively low. However, if GR is properly supported because policy makers realize its potential, then the simulated high impact scenario is a realistic outcome, with significant positive nutrition and health effects, especially among the poor.

Our analysis is *ex ante* in nature. Future research will have to determine the exact size of crucial parameters, like the β-carotene content in the rice grain that can be realized under field conditions, the magnitude of post-harvest losses of β-carotene, or its bioavailability. Another important question is to what extent high levels of β-carotene in rice are compatible with agronomic properties or other characteristics that are important to consumers. Beside sufficient support for social marketing activities, this will influence technology acceptance. Finally, the safety of GR for human consumption and the environment will have to be assessed, and the technology needs to be approved by the national food safety and biosafety authorities before it can be distributed to local rice farmers and consumers.

NOTES

1. There are also other approaches available to quantify the disease burden, including cost-of-illness or willingness-to-pay estimates. In our context, the DALYs approach is considered more equitable, because it is not directly influenced by the earnings of individuals. In cost-of-illness calculations, the income of individuals matters in form of the opportunity cost of the time they are ill, that is, ill individuals with high incomes cause higher costs than ill individuals with low incomes. Likewise willingness-to-pay estimates depend on income levels, as demand for health is associated with a positive income elasticity.

2. Biofortification refers to the breeding of staple crops for higher levels of vitamins and minerals that are essential for human nutrition and health (Bouis, 2002); this approach contrasts with industrial fortification efforts that focus on processed foodstuffs. Apart from

β-carotene, plant breeders also work on enhancing iron and zinc contents in staple food crops. We have also developed similar impact assessment methodologies for these other micronutrients (Stein *et al*., 2005).

3. We only consider health outcomes for which the causality of VAD is established beyond reasonable doubt; individual studies suggest further adverse functional outcomes of VAD, but causality has not been shown conclusively (cf. Stein *et al*., 2005).

4. Prevalence rates (''stock''), which are often given in health statistics, can be transformed into incidence rates (''flow'') that are required by the DALY formula (Stein *et al*., 2005).

5. Although we make projections over 30 years, we base these projections on static incidence rates. This might produce an overestimate of the benefits of GR if the incidence rates fall with rising incomes and urbanization. However, this development is expected to be counteracted by rising absolute population figures, that is, even though in future there may be relatively less people suffering from VAD, their absolute number is not expected to decrease. Hence, instead of adding more layers of different assumptions that are expected to cancel each other out on the whole, we have tried to keep our assumptions simple and transparent wherever there is no obvious benefit of higher complexity.

6. Plant food does not contain any VA but only VA precursors, mainly β-carotene; whenever we talk about ''VA intake'' we mean the actual VA intake from animal source foods *and* the β-carotene intake from all foods, which we converted into units of VA by using a rate of 12:1 (IOM, 2002).

7. We use the EARs of the Institute of Medicine (IOM, 2000) as these provide the most recent and detailed set of requirements available. For an explanation of the different concepts of EARs and ''recommended dietary allowances'' (RDAs) and their correct use, see IOM (2000) and Barr *et al*. (2002).

8. The average monthly *per capita* consumption of rice in rural India is 6.8 kg (NSSO, 2000). Of course this masks regional and socioeconomic differences, which are taken care of in the analysis through the use of nationally representative household data.

9. Companies that hold intellectual property rights (IPRs) on different technology components have agreed to waive royalties when GR is grown by farmers whose annual income is less than US$10,000 (Paine *et al*., 2005; Potrykus, 2001). According to the representative household survey (NSSO, 2000), only 0.02% of rural households in India have annual incomes (approximated by expenditures) above US$10,000. Problems with IPRs would only occur if GR is exported to high-income countries. However, given the yellow color of the grain, such exports could easily be traced. In 2003, India exported only 3.75% of its rice production (FAO, 2004).

10. The survey we used (NSSO, 2000) recorded the consumption from ration shops and school feeding programs separately. For the school meals we assume that outside the predominantly wheat-eating states (Haryana, Punjab, Rajasthan, Uttar Pradesh, Uttaranchal, Chandigarh, Delhi) each meal includes 100 g of GR when GR is served.

11. As we only consider those health consequences of VAD for which there is broad scientific consensus, our calculated burden of VAD might underestimate the true burden, if we omitted outcomes that are actually caused by VAD but for which this causality is not proven yet. This would also lead to higher positive impact of GR. Therefore, our results are rather on the conservative side.

12. Predominantly rice-eating states include Andhra Pradesh, Arunachal Pradesh, Assam, Goa, Kerala, Manipur, Meghalaya, Mizoram, Nagaland, Orissa, Sikkim, Tamil Nadu, Tripura, West Bengal, Andaman & Nicobar Islands, Lakshadweep, and Pondicherry.

13. From a theoretical point of view it would be more appropriate to use purchasing power parity dollars throughout. However, this would greatly reduce the comparability of our results with most other studies as results are usually reported in US$. Also, about half of the costs occur at the international level and are paid for in US$, while part of the national costs were estimated by experts who also reported the costs in US$.

14. See Table 2 for details of the assumptions in the initial low and high impact scenarios.

15. An additional analysis using a ''conventional'' conversion rate for β-carotene into VA of 12:1 in the low impact scenario shows that 112,000 DALYs and 3,000 lives could be saved each year through the consumption of GR, which corresponds to a reduction of the burden of VAD in India of 4.8%. While under these very pessimistic assumptions the impact on the burden of VAD is rather small, at US$35.47 per DALY saved the cost-effectiveness of the intervention still remains very competitive with regard to the alternatives.

16. The authors of the study do not themselves suggest that the colored rice varieties could be used to control VAD effectively, but their study is used by Greenpeace in that regard.

REFERENCES

Adamson, P. (2004). Vitamin & mineral deficiency. Ottawa: The Micronutrient Initiative <http://www.micronutrient.org/reports/report.asp?cntry=Full>.

Barr, S. I., Murphy, S. P., & Poos, M. I. (2002). Interpreting and using the Dietary Reference Intakes in dietary assessment of individuals and groups. *Journal of the American Dietetic Association, 102*, 780–788. <http://dx.doi.org/10.1016/S0002-8223(02)90177-X>.

Barry, G. (2005). Personal communication. Co-ordinator of the Golden Rice Project, International Rice Research Institute, Los Baños.

Beyer, P. (2005). Personal communication. Professor at the Department of Cell Biology at the Centre for Applied Biosciences, University of Freiburg, Freiburg.

BLS (2005). *Inflation calculator*. Washington, DC: US Department of Labor, Bureau of Labor Statistics. <http://data.bls.gov/cgibin/cpicalc.pl>.

Bouis, H. E. (2002). Plant breeding: A new tool for fighting micronutrient malnutrition. *Journal of Nutrition, 132*, 491S–494S. <http://jn.nutrition.org/cgi/content/abstract/132/3/491S>.

Bouis, H. E. (2005). Personal communication. Director of HarvestPlus, International Food Policy Research Institute, Washington, DC.

Buckland, H. (2005). The oil for ape scandal: How palm oil is threatening orang-utan survival. London: Friends of the Earth Trust. <http://www.foe.co.uk/resource/reports/oil_for_ape_full.pdf>.

Dawe, D., Robertson, R., & Unnevehr, L. (2002). Golden rice: What role could it play in alleviation of vitamin A deficiency?. *Food Policy, 27*, 541–560. <http://dx.doi.org/10.1016/S0306-9192(02)00065-9>.

Dubock, A. (2005). Personal communication. Biotechnology collaborations and humanitarian donations of technology, Syngenta International, Basel.

Erhardt, J. (2005). Vitamin A intake calculator. Basel: Sight and Live. <http://nutrisurvey.de/vac/vac.htm>.

FAO (2004). FAOSTAT data. Rome: Food and Agriculture Organization. <http://faostat.fao.org/faostat/collections> (January 2006).

Frei, M., & Becker, K. (2004). On rice, biodiversity & nutrients. Stuttgart: Institute of Animal Production in the Tropics and Subtropics, University of Hohenheim. <http://www.greenpeace.org/raw/content/international/press/reports/rice-biodiversity-nutrients.pdf>.

Gopalan, C., Rama Sastri, B. V., & Balasubramanian, S. C. (1989). Nutritive value of Indian foods. Hyderabad: Indian Council of Medical Research.

Greenpeace (2005). Golden Rice: All glitter, no gold. Amsterdam: Greenpeace International <http://www.greenpeace.org/international/news/failures-of-golden-rice>.

Grusak, M. A. (2005). Golden Rice gets a boost from maize. *Nature Biotechnology, 23*, 429–430. <http://dx.doi.org/10.1038/nbt0405-429>.

Haddad, L., Alderman, H., Appleton, S., Song, L., & Yohannes, Y. (2003). Reducing child malnutrition: How far does income growth take us? *World Bank Economic Review, 17*, 107–131. <http://wber.oxfordjournals.org/cgi/content/abstract/17/1/107>.

IIPS (2000). National Family Health Survey (NFHS-2), 1998–99: India. Mumbai: International Institute for Population Sciences and ORC Macro. <http://www.nfhsindia.org/pnfhs2.html> (July 2006).

IOM (2000). Dietary Reference Intakes: Applications in dietary assessment. Institute of Medicine. Washington, DC: National Academy Press. <http://www.nap.edu/books/0309071836/html/>.

IOM (2002). Dietary reference intakes for vitamin A, vitamin K, arsenic, boron, chromium, copper, iodine, iron, manganese, molybdenum, nickel, silicon, vanadium, and zinc. Institute of Medicine. Washington, DC: National Academy Press. <http://www.nap.edu/books/0309072794/html/>.

Mayer, J. E. (2005). Personal communication. Golden Rice Project Manager Campus, Technologies Freiburg, University of Freiburg, Freiburg.

Murphy, S. P., & Poos, M. I. (2002). Dietary Reference Intakes: Summary of applications in dietary assessment. *Public Health Nutrition, 5*, 843–849. <http://dx.doi.org/10.1079/PHN2002389>.

Murray, C. J. L., & Lopez, A. D. (1996). *The Global Burden of disease* (vol. 1). Cambridge, MA: Harvard University Press. <http://www.who.int/healthinfo/bod1990study/en/index.html>.

Narasinga Rao, B. S. (2000). Potential use of red palm oil in combating vitamin A deficiency in India. *Food and Nutrition Bulletin, 21*(2), 202–211. <http://www.unu.edu/unupress/food/Unupress.htm#bulletin>.

Nestel, P., Bouis, H. E., Meenakshi, J. V., & Pfeiffer, W. (2006). Biofortification of staple food crops. *Journal of Nutrition, 136*, 1064–1067. <http://jn.nutrition.org/cgi/content/abstract/136/4/1064>.

NSSO (2000). Consumer expenditure survey 1999/2000, 55th Round. Calcutta and New Delhi: National Sample Survey Organisation. <http://mospi.nic.in/mospi_about_nsso.htm>.

Nuffield (2003). The use of genetically modified crops in developing countries. Discussion Paper. Nuffield Council on Bioethics, London. <http://www.nuffieldbioethics.org/fileLibrary/pdf/gm_crops_paper_final.pdf>.

Paine, J., Shipton, C. A., Chaggar, S., Howells, R. M., Kennedy, M. J., Vernon, G., *et al.* (2005). Improving the nutritional value of Golden Rice through increased pro-vitamin A content. *Nature Biotechnology, 23*, 482–487. <http://dx.doi.org/10.1038/nbt1082>.

Planning Commission (2002). Tenth Five Year Plan (2002–2007), vol. II, chap. 3.3. Government of India, New Delhi. <http://planningcommission.nic.in/plans/planrel/fiveyr/10th/default.htm>.

Potrykus, I. (2001). Golden Rice and beyond. *Plant Physiology, 125*, 1157–1161. <http://www.plantphysiol.org/cgi/content/full/125/3/1157>.

Rao, S. R. (2005). Personal communication. Department of Biotechnology, Ministry of Science and Technology, New Delhi.

Registrar General (1991 & 2001). Census of India. New Delhi: Government of India. http://www.censusindia.net.

Ruel, M. T. (2001). *Can food–based strategies help reduce vitamin A and iron deficiencies?. Food Policy Review No. 5*. Washington, DC: International Food Policy Research Institute. <http://www.ifpri.org/pubs/fpreview/fpreview05.htm>.

Russell, R. M. (2006). Personal communication. Professor of Medicine and Nutrition and Director of the Jean Mayer USDA Human Nutrition Research Center on Aging. Tufts University, Boston, MA.

Shiva, V. (2000). *The 'Golden Rice' hoax*. Pottergate: Norfolk Genetic Information Network. <http://ngin.tripod.com/11.htm>.

Singh, A. K. (2005). Personal communication. Division of Genetics. Indian Agricultural Research Institute, New Delhi.

Sommer, A., & West, K. P. Jr. (1996). *Vitamin A deficiency: Health, survival, and vision*. New York, NY: Oxford University Press.

Stein, A. J. (2006). *Micronutrient malnutrition and the impact of modern plant breeding on public health in India: How cost-effective is biofortification?* Göttingen: Cuvillier Verlag. <http://www.cuvillier.de/flycms/de/html/30/-UickI3zKPS,ydkw=/Buchdetails.html>.

Stein, A. J., Meenakshi, J. V., Qaim, M., Nestel, P., Sachdev, H. P. S., & Bhutta, Z. A. (2005). Analyzing the health benefits of biofortified staple crops by means of the disability-adjusted life years approach. HarvestPlus Technical Monograph No. 4. Washington, DC and Cali: International Food Policy Research Institute and International Center for Tropical Agriculture. <http://www.harvestplus.org/pubshp.html>.

Stein, A. J., Sachdev, H. P. S., & Qaim, M. (2006). Potential impact and cost-effectiveness of Golden Rice. *Nature Biotechnology, 24*(10), 1200–1201. <http://dx.doi.org/10.1038/nbt1006-1200b>.

Talukder, A., Kiess, L., Huq, N., de Pee, S., Darnton-Hill, I., & Bloem, M. W. (2000). Increasing the production and consumption of vitamin A-rich fruits and vegetables: Lessons learned in taking the Bangladesh homestead gardening programme to a national scale. *Food and Nutrition Bulletin, 21*(2), 165–172. <http://www.unu.edu/unupress/food/Unupress.htm#bulletin>.

Tan-Torres Edejer, T., Aikins, M., Black, R., Wolfson, L., Hutubessy, R., & Evans, D. B. (2005). Cost effectiveness analysis of strategies for child health in developing countries. *British Medical Journal, 331*, e1177. <http://dx.doi.org/10.1136/bmj.38652.550278.7C>.

Tan-Torres Edejer, T., Baltussen, R., Adam, T., Hutubessy, R., Acharya, A., Evans, D. B., *et al.* (2003). *Making choices in health: WHO guide to cost-effectiveness analysis*. Geneva: World Health Organization. <http://www.who.int/choice/publications/p_2003_generalised_cea.pdf>.

Toteja, G. S., Singh, P. (2004). Micronutrient profile of the Indian population. CD-Rom. MOST/USAID and Indian Council of Medical Research, New Delhi.

UN SCN (2004). Fifth Report on the World Nutrition Situation. United Nations System, Standing Committee on Nutrition, Geneva. <http://www.unsystem.org/scn/Publications/html/RWNS.html>.

UNICEF (2003). *The state of the world's children 2004*. New York, NY: United Nations Children's Fund. <http://www.unicef.org/sowc04/>.

USDA (2004). *National nutrient database for standard reference. Release 17*. Washington, DC: US Department of Agriculture. <http://www.nal.usda.gov/fnic/foodcomp>.

WHO (2001a). *Life tables for 191 countries: World mortality 2000*. Geneva: World Health Organization. <http://www3.who.int/whosis/life/>.

WHO (2001b). *Macroeconomics and health: Investing in health for economic development*. Geneva: World Health Organization. <http://www.who.int/cmhreport/>.

World Bank (1993). World Development Report. World Bank, Washington, DC. <http://econ.worldbank.org/wdr/>.

World Bank (2004). *World Development Indicators database: India data profile*. Washington, DC: World Bank. <http://www.worldbank.org/data/countrydata/countrydata.html>.

Ye, X., Al-Babili, S., Klöti, A., Zhang, J., Lucca, P., Beyer, P., *et al.* (2000). Engineering the provitamin A (β-carotene) biosynthetic pathway into (carotenoid-free) rice endosperm. *Science, 287*, 303–305. <http://dx.doi.org/10.1126/science.287.5451.303>.

Zimmermann, R., & Qaim, M. (2004). Potential health benefits of Golden Rice: A Philippine case study. *Food Policy, 29*, 147–168. <http://dx.doi.org/10.1016/j.foodpol.2004.03.001>.