Reversing Productivity Losses from Iron Deficiency: The Economic Case[1,2,3]

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ABSTRACT Iron deficiency anemia (IDA) depresses human productivity, but policymakers do not generally view this effect as an impediment to sustained economic growth. Economic logic should be enfolded in public advocacy for increased investment in the prevention and control of IDA. This paper argues that integrated strategies are required, with each intervention clearly related to particular groups at risk, and benefits carefully calibrated with costs. Protecting women's lives through supplementation has the first call on public resources, but the most productive investments reduce population prevalence at least cost, and these lie with food-based approaches within the competence of the processed food and seed industries. The public and private sectors must embark on modernization of the food industry in developing countries and reorientation of the international agricultural research complex so that iron-enriched essential foods will be affordable and accessible to the poor, especially children. The costs of IDA, the availability of cost-effective strategies and the benefits of sustained iron nutrition improvement to individuals, families and nations are reviewed. The roles of iron supplementation, food fortification, plant breeding and biotechnology, both actual and imminent, are described. The paper concludes that a recast Green Revolution directed toward dietary quality may be the key to enhancing the learning and earning capacity of young people in the developing world. J. Nutr. 132: 794S–801S, 2002.

KEY WORDS: • *iron deficiency anemia* • *economic* • *policy* • *plant breeding*

A compelling public policy problem: why is there no investment clout?

"No other technology [iron fortification and supplementation] offers as large an opportunity to improve lives . . . at such a low cost and in such a short time . . ." (1)

"Finding sustainable solutions to micronutrient malnutrition will not be forthcoming in the foreseeable future if we do not start to adopt agriculturally based tools, such as plant breeding, to this important global crisis in human health and well being" (2).

Among the "hidden hunger" issues that developing countries face today, none is more compelling than the pervasive and puzzling problem of iron deficiency (ID)[5] and its clinical form, iron deficiency anemia (IDA). Half of the preschool children in developing countries are anemic, compared with only 7% in developed countries. Asia is responsible for three fourths of the world's ID problem, which affects two billion people. In Asia, IDA affects 60% of women of reproductive age, and 40–50% of preschoolers and primary graders. New hotspots have emerged, such as Central Asia, where IDA has increased at an alarming rate.

Maternal mortality may be 20 times greater in developing compared with developed countries, in part because severe anemia causes maternal deaths (3,4). Avoidable maternal deaths and poor learning among school children are two common and important consequences of IDA.

The persistence of ID, particularly its neglect, is puzzling because it is a public policy problem of the first order, given its effect on the economic potential of individuals, families and nations as demonstrated below. The question is why economic planners in developing countries are not particularly concerned about it, and why donors and other development partners have put the problem on the back burner for years. Our challenge at this important conference is to recover the sense of urgency that has brought us together and to compare strategies on engaging the investment decision makers and persuading them to do more.

One explanation for delayed recognition is the difficulty policy makers have in perceiving ID as an urgent problem with a simple, proven solution. Anemia's effects are subtle and insidious, less striking and therefore more difficult for policymakers to grasp and act upon. Vitamin A and iodine deficiencies have stark and visible consequences that compel policy makers to direct attention, as do nutritional emergencies. This

[1] Presented at the Atlanta conference on Forging Effective Strategies to Combat Iron Deficiency held May 7–9, 2001 in Atlanta, GA. The proceedings of this conference are published as a supplement to *The Journal of Nutrition.* Supplement guest editors were Frederick Trowbridge, Trowbridge & Associates, Inc., Decatur, GA and Reynaldo Martorell, Rollins School of Public Health, Emory University, Atlanta, GA.

[2] This article was commissioned by the International Life Sciences Institute Center for Health Promotion (ILSI CHP). The use of trade names and commercial sources in this document is for purposes of identification only and does not imply endorsement. In addition, the views expressed herein are those of the individual authors and/or their organizations and do not necessarily reflect those of ILSI CHP.

[3] Portions of this paper were discussed in (24).

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[5] Abbreviations used: ADB, Asian Development Bank; CGIAR, Consultative Group for International Agricultural Research; DALY, disability-adjusted life years; EFA, Education for All; GDP, gross domestic product; ID, iron deficiency; IDA, iron deficiency anemia; IDD, iodine deficiency disorders; IDG, International Development Goals; PEM, protein-energy malnutrition; SFIT, Swiss Federal Institute of Technology; TCCA, Trans-Caucasus Central Asia.

is an obvious point, but ID requires a special kind of advocacy that looks at short-, medium- and long-term effects of iron from a life-cycle perspective, including economic losses.

Economists have not always helped, most often equating food security with energy sufficiency, calculating energy consumed and neglecting negative trends in the dietary quality of the poor. All that must change if iron is to be give its just due.

To position the economic case, the main arguments are the following: anemia control is a global economic priority; mortality and economic costs are poorly understood but are substantial; productivity losses arising from poor endurance in physically demanding occupations lead to lower wages; but cognitive effects that persist from childhood exceed physical productivity effects on adult productivity, although both are considerable even in low income countries; and as incomes rise across the world, cognitive losses become a key economic issue, particularly for young children.

Whether it is supplementation, fortification or plant breeding, multiple nutrient interventions are far better than monovalent approaches. Integrated strategies can be made cost-effective, but they must be properly coordinated, reflecting the effectiveness and cost of each intervention. The emerging partnership of agricultural research and technology, along with food fortification through the processed food industry, potentially offers the optimal benefits of low cost on a sustainable basis. The long-term solution to IDA is a more diverse diet, but fortification can have an effect in the interim for the population as a whole, and may well remain the long-term solution for particular vulnerable groups that cannot obtain enough iron even from an ample and varied diet. Public policy advocacy should link anemia reduction to maternal and child development, and in turn to sustainable economic development.

The argument presented in the paper is that three directions for investment to improve iron nurtriture surpass all others, optimizing benefits at least cost. First, the fortification of essential foods is a pro-poor investment that will prevent micronutrient deficiencies and improve child growth and development through a "dietary revolution" sustained through market based solutions. Second, agricultural research, through nutrition focused plant breeding and biotechnological applications, also has great potential. The third pathway is through integrated programs targeting young children in which industry's contribution is balanced by the commitment of public health to nutrition surveillance of at-risk groups, public education to shift patterns of consumption especially for infants and dietary diversification through agricultural sector reform.

Forging an effective public-private partnership. Food fortification is an essential element of national food policies in Asian and Pacific countries to ensure nutrition security for all their citizens. Both food industry producers and consumers should be fully informed about the minimal change in production or purchasing decisions required to shift preferences and demand toward fortified foods. The technical costs of production are not prohibitive. The public sector has a major role to ensure quality assurance and a level playing field for all producers, and to assist the shift to fortified staples with aggressive social marketing to the less affluent. This is proper use of public resources because it has a preventive health thrust and will allow people's needs to be felt and expressed. The result will be informed choices by all groups of society.

New opportunities in plant breeding and biotechnology are also opening horizons that may contribute substantially to the elimination of micronutrient malnutrition in the foreseeable future. Investing in fortified staples and in plant breeding research will strengthen the capacity of the food and agriculture industries as global trading partners. The processed food and seed industries stand poised to initiate the second Green Revolution, addressing dietary quality to benefit the health of poor mothers and the mental development of their children within the next decade.

The arguments concerning why governments and the private sector should invest in this are obvious, but worth stating. Companies should invest because the raising of product quality will stimulate competition and trade. Economies of scale for fortified products will lower prices and reach new consumers, overcoming chronic iron undernutrition, and will raise the general wage and consumer spending. Targeting fortified foods to poor women and children will improve their physical and mental development, raise earnings of the labor force, create demand and give back to the community in a win-win situation.

Rationale for investing in elimination of iron deficiency

Addressing patterns of harm and lost human potential caused by the persistence of IDA is a global governance concern because raising the prospects of poor children will help to make global justice and peace possible. The economic rationale is that society's investment can enhance productivity, efficiency and social equity.

IDA prevention and control places strong emphasis on human development policies that share the opportunities for growth and fruits of development with the children of the poor. Well developed children will be more productive, contributing citizens. The reasons for investing in the human potential of poor children are both compelling and self-evident, and the IDA question should be positioned squarely at the juncture of human development and economic growth.

There are strong economic and social arguments supporting increased investment in iron adequacy for women and their children. First, iron enrichment will enhance human development and reduce poverty sustainably. The most critical period of brain development is in the first 3 y of life, and proper iron nutrition is a critical factor in neurosensory integration of the infant brain. Optimal development will be promoted by ensuring adequate nutrition, including iron, during infancy up to age three—and even before birth by providing adequate health and nutrition for the pregnant mother. Second, improved iron status of children raises the efficiency of public expenditure in health and education, lowering illnesses and dropouts, and reduces the need for public resources to compensate later on. Third, reversing IDA in children strengthens the prospects of long-term economic competitiveness and future quality and productivity of the labor force. Expanding the capacity for learning and the potential for achievement for each child in school and later the adult in the workplace raises wages of the worker, increases permanent income of the family, permits higher investment in the quality of the next generation and shifts the major fiscal responsibility of raising children from the state to families, communities and the private sector. Fourth, iron enrichment programs can correct or compensate for the historic social biases against girl children, their risks in pregnancy, special needs for iron adequacy and greater likelihood of dropping out of school.

The Education for All (EFA) evaluation in Dakar (5) stressed that the difficulties in universal primary school enrollment due to the poor readiness of undernourished children for schooling were not anticipated. Primary dropout and retention rates have not improved greatly in the last decade despite major investments in school systems, and it is plausible to argue that poor iron nurtriture dulls learning capacity and lies at the heart of the weak demand side of EFA.

The remaining sections review the costs of doing very little for preventing IDA in women and children, i.e., preventable deaths, lowered schooling achievement, productivity and economic growth. On the positive side, the cost-effectiveness and high rates of return on iron enrichment programs, especially for young children, are reviewed.

Meeting International Development Goals (IDG). Children lie at the heart of international commitments to social justice. Asian governments have pledged at international forums to provide health and nutrition for all children and their mothers, and to guarantee essential education as a human right as well as the key to equitable growth and sustainable development. Yet these pledges have been far from realized, because the levels of investment in social services are hardly commensurate with the need, in part because all too often systems are served rather than the child. Investing in the elimination of anemia in women and children will help nations meet the IDG to which they have subscribed. Three of the seven IDG to be achieved by 2015 relate directly to children: 100% primary school enrollment rate, elimination of gender disparities in primary and secondary education and reduction in maternal, infant and child mortality by two thirds. Two other IDG target maternal health, a prerequisite for healthier children. Anemia is very much implicated in the mortality of women and the cognition of children, and undermines the efficiency and equitable basis for public health and education investments. IDA reduction will enhance educability and labor productivity, will capture intergenerational benefits as we recognize even more the need to intervene in adolescence to protect young women's health and safety during first pregnancy, and will sustain economic growth in combination with sound economic policies.

Avoiding deaths. Using Asia as an example, improving maternal and child iron status is essential to accomplish the mortality reduction goal. One estimate is that up to a fifth of maternal deaths in nine low income Asian countries, 65,000 deaths annually, are caused by severe IDA (6) and the interplay of underweight, stunting and iron deficiency has an effect on the mortality of young children. Low birth weight infants often suffer illness complicated by iron problems, are far more likely to die, and stunting combined with IDA is implicated in very high rates of dropout and retention rates in primary schooling.

Productivity gains. The direct productivity effects of malnutrition are on the capacity to perform physical work and on earning ability. Protein energy malnutrition (PEM), stunting and IDA reduce both. Improvements in iron increase the capacity to perform moderate to hard labor with related increases in wages. These effects have been demonstrated in India, Indonesia, the Philippines and other countries (7–13). The Asian Development Bank (ADB)-UNICEF study in low income Asia estimated that productivity losses for manual laborers are up to 9% for severely stunted workers; losses from IDA are 17% for workers engaged in heavy physical labor and 5% for moderately active workers. Losses due to cognitive deficits for malnourished children were 10% for stunted individuals, 4% for IDA, and 10% for iodine deficiency disorders (IDD) (6). This translates into a staggering sequence of losses in growth and human potential for developing countries.

Cognitive gains. The indirect productivity effects of improved iron status are on cognitive ability and achievement, through impact on mental and motor skills in infants and on cognition, learning and behavior in children and adolescents (14). Moreover, long-term studies of subjects followed from infancy to as late as adolescence show that anemia in early life, indicating a state of severe chronic iron deficiency, leads to poorer overall cognitive functioning and lower school achievement test scores later in life, even when the anemia in infancy had been corrected (14). In addition to IDA, PEM and IDD also have a substantial negative effect on cognition, behavior and achievement; in all three cases, the effects produced by chronic deficiencies in the early years are manifested later in life, underscoring the need for prevention.

Raising economic growth rates. There are several credible estimates of the economic costs of IDA in developing countries. The ADB and UNICEF conducted a seven country Asian study on the pernicious effects of undernutrition in children (15,16). The general conclusion was that malnutrition, with its insidious effects over the life span of the child, would cost the economy at least 3% of gross domestic product, based on conservative assumptions (a "low scenario" built into the model). Looking at South Asia, the region with the highest prevalence of IDA, one can see a loss of ~2% in economic growth, and even though the cognitive effects in low income countries are muted downward by the low wages in the region, they are nevertheless very substantial. Ross and Horton (17) estimate that Bangladesh alone loses 2% of its gross domestic product (GDP) to iron deficiency, and South Asia loses $5 billion annually. These would grow proportionately larger in Southeast and East Asia where wages are higher because cognition, schooling achievement and wage level are related. India, for example, loses growth from two directions: adult productivity (3%) from PEM, iodine deficiency and IDA, and from IDA induced cognitive impairment (~1%).

It is likely that in higher income developing countries, the cognitive effects of IDA on earnings and national economic growth are dominant over physical productivity effects, and these effects increase proportionately according to average wages and per capita income in developing countries. The higher the country's per capita income, the more damaging is the effect on economic growth. The World Bank's figure of 5% GDP loss for all micronutrient deficiencies (1) is probably understated, based on these estimates for IDA alone. **Figure 1** examines the productivity and cognitive losses of IDA in low income South Asia (6).

Returns on investment to improve iron nurtriture

The case for iron supplementation. The effectiveness of iron supplementation programs (both daily and weekly) to raise hemoglobin and serum ferritin levels has been demonstrated (4,18,19). Cost-effective nutrition interventions are available and should be used more consistently (6,18,20,21). Expressed in terms of disability-adjusted life years (DALY),[6] or healthy years of life saved, the following iron-enriched interventions are among the lowest priced at <$25/DALY: breastfeeding promotion; both daily and weekly oral iron for pregnant women; parallel health interventions at similar cost are school health (particularly iron supplements integrated with deworming medication); and health, nutrition and family planning information and education campaigns. Please note the obvious synergies in promoting joint health and nutrition interventions for iron improvement in mothers and their young children in the form of family based packages of services. Education and supplementation must be linked, along

[6] DALY is a composite index of health linked to a productive life usually referred to as a "year of healthy life saved." DALY is a weighted index that takes into account loss of life, morbidity and disability, and their collective effect on productivity.

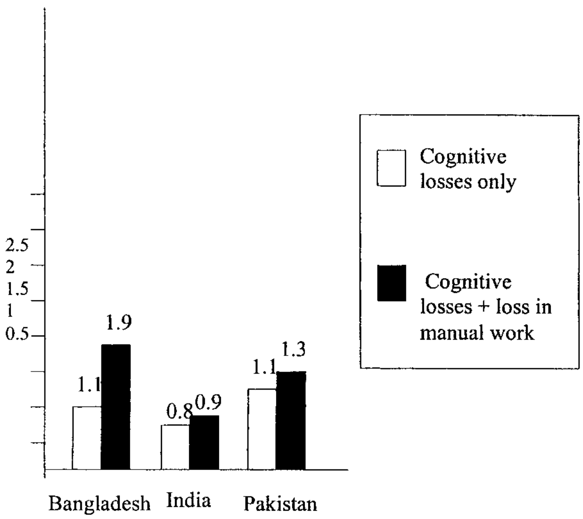

FIGURE 1 Percentage lost in gross domestic product (GDP) due to iron deficiency. Source: Ref. (6).

with superior logistics and management, for iron enrichment programs to be effective (22). At a higher price, there are four iron relevant interventions at <$75/DALY: improved weaning practices for infants, improved complementary feeding practices for young children, food supplements for pregnant women and the nutrition component of the Integrated Management of Childhood Illness (20). Unquestionably, iron supplementation is competitive with the most cost-effective options available to primary health care, as long as management systems are in place and education supports informed consent and voluntary compliance.

The case for iron fortification. The World Bank (1) has summarized the benefits of micronutrients in terms of cost per life saved and productivity gained for iron supplementation and iron fortification programs (**Table 1**). For saving lives at least cost (i.e., *private benefit to at-risk persons*), targeted iron supplementation to pregnant mothers is more cost effective than iron fortification of flour or another staple ($800 vs. $2000), although the latter is a more sustainable solution in the long run as incomes rise and households gain access to higher quality primary health care.

From the perspective of enhanced productivity delivered by programs (i.e., *efficient use of resources*), where productivity is defined as the least-cost discounted method of reducing clinical deficiency in the population, iron fortification is clearly the public policy choice. Fortification is three times as productive as iron supplementation for pregnant women. Fortification yields $84 per dollar invested in reducing IDA prevalence, whereas targeted supplementation for pregnant women yields $25. Thus, the population wide effect is greatly increased by fortification. Consistent findings for Vitamin A and iodine also exist (1).

The last measure is *the social benefit cost per DALY or healthy life year saved.* Fortification is three times more effective than supplementation, costing $4 vs. $13/DALY saved. This is a social benefit because of the avoided losses in life and productivity to society, and rehabilitation costs that the state and the family would have to bear if incurred. The unit costs drawn from the seven-country Asian study by ADB and UNICEF (6) show that micronutrient supplementation is affordable, but fortification is one tenth the cost or less. Iron supplements for a full pregnancy cost ~$2. Annual iodine and iron fortification costs are $0.05 and $0.10 per person, respectively. The cost of putting iron and other essential vitamins and trace minerals through an appropriate mix of fortified essential staples in an economy is <$0.50/(person · y). That is ~4% of WHO's recommended minimum $12 package of primary health care services for developing countries. Because micronutrient enrichment is as effective in preventing illness, disability and death as is primary health care, there will be no sensible argument against fortification as long as the public is aware of the benefits.

In summary, the economic benefits of fortification are reduced morbidity, improved work capacity and improved cognitive effects. Reduced morbidity will reduce health care costs and days lost in school or at work; improve school attendance, concentration and performance; and strengthen both production and consumption benefits. Reduced public health and public education expenditure, and reduced school dropout and retention rates will increase efficiency of public investment for essential social services and free resources for better uses. The economic value of fortification is expressed in improved work output due to increased work capacity and improved marginal productivity of labor. Last, improved cognitive ability will allow realization of the benefits of education expenditure; raise the number of years of schooling and academic performance; and, in a growing economy, will also raise wages and household income invested in the quality of the next generation of children.

The case for biofortification. *Plant breeding.* The plant breeding strategy for micronutrient-enriched germplasm offers the opportunity to create an international public good through comprehensive benefits to producers and consumers with public health significance (23,24). Given the high payoffs to reducing micronutrient deficiencies and the current reservations about conventional approaches to solve the problem quickly and completely, plant breeding should be tried because of its potential coverage of entire Asian populations deriving most of their consumption from rice, especially the poor. Because the poor consume large amounts of staple foods on a daily basis, the prospect of improving nutrition status is encouraging if a high proportion of the domestic production of food staples can be provided by nutritionally improved vari-

TABLE 1

Returns on improving iron status[1]

Remedy	Cost per life saved (US$)	Discounted value of productivity gained per program (US$)	Cost per DALY[2] gained (US$)
Supplementation of pregnant women only	800	25	13
Fortification	2000	84	4

[1] Source: Adapted from the World Bank, Enriching Lives (1994).
[2] DALY, disability-adjusted life year.

eties. The breeding strategy does not depend on shifts in behavior or preferences. Biotechnology offers considerable promise, as reviewed by Bouis (23).

Results so far obtained under the Micronutrients Project, sponsored by the Consultative Group for International Agricultural Research (CGIAR), indicate that the breeding parameters are not difficult and are highly likely to be low cost. In particular, *1*) adequate genetic variation in concentrations of β-carotene, other functional carotenoids, iron, zinc, and other minerals exists in the major germplasm banks to justify selection; *2*) micronutrient-density traits are sufficiently stable across growing environments; *3*) in all crops studied, it is possible to combine the high micronutrient-density trait with high yield, unlike protein content and yield, which are negatively correlated; *4*) genetic control is simple enough to make breeding economic and it should be possible to improve the content of several limiting micronutrients together, thus pushing populations toward nutritional balance; and *5*) bioavailability tests using animals are encouraging but tests using human subjects are a high priority (25).

High benefits to costs. Importantly, high trace mineral density in seeds produces more viable and vigorous seedlings in the next generation, and efficiency in the uptake of trace minerals improves disease resistance and agronomic characteristics, which in turn improve plant nutrition and productivity in trace mineral deficient soils. Farmer adoption and spread of nutritionally improved varieties can rely on profit incentives, either because of agronomic advantages on trace mineral deficient soils or incorporation of nutritional improvements in the most profitable varieties being released. Because staple foods are eaten in large quantities every day by the malnourished poor, delivery of enriched staple foods (fortified by the plants themselves during growth) can rely on existing consumer behavior. Benefits to relatively small investments in agricultural research can be disseminated widely, potentially accruing to hundreds of millions of people and millions of hectares of croplands across countries and across time. Thus, the combined benefits for human nutrition and agricultural productivity resulting from breeding staple food crops that are more efficient in the uptake of trace minerals from the soil and that load more trace minerals into their seeds, result in extremely high ex ante estimates of benefit/cost ratios for investments in agricultural research in this area. Other complementary strategies run recurrent costs on a continuing basis, which decline slowly over time and increase proportionately with geographic coverage.

Because biofortification is a new strategy, definitive studies of the effect of this approach must await the efficacy and effectiveness trials. An interdisciplinary consortium of collaborating partners, organized by the CGIAR, will likely conduct these studies. In general, however, poor consumers in developing countries acquire roughly one half of their total iron intake (and a higher percentage of zinc intake) from staple foods. Results from germplasm screening suggest that the iron and zinc content of staple foods can be doubled through conventional breeding. This in turn implies that iron and zinc intakes can be increased by a minimum of 50% in poor people's diets. This should result in an appreciable improvement in nutrition and health even for those whose intakes remain below recommended daily rates.

An example of the enormous economic benefits of the biofortification strategy based on numbers for India and Bangladesh is given in Appendix 1. This example is based on development of iron and zinc dense varieties of rice and wheat. The somewhat conservative assumptions suggest that the undiscounted returns that come on-stream during the second decade of research and development would be ~$4.9 billion on a total investment of $42 million, $1.2 billion in benefits from better nutrition and $3.7 billion in benefits from higher agricultural productivity.

A more formal benefit cost ratio evaluation, in which the ratio of the present value of benefits divided by the present value of costs, at a 3% discount rate (commonly used for social benefits), for returns to better iron nutrition in humans is ~19, similar to that found by Horton and Ross (26) for fortification in South Asia. This ratio rises to 79 if benefits to higher agricultural productivity are included. A different way of expressing the concept of discounting over time is the internal rate of return, in which the interest rate, at which benefits equal costs plus interest if the funds were borrowed to make the investment, is calculated. In this case the internal rate of return is 29% if only benefits to human nutrition are considered and 44% if benefits to both human nutrition and higher agricultural productivity are considered.

It is important to point out that these minimum effects are what can be documented with evidence presently available with respect to the use of conventional breeding techniques following a strategy of increasing trace mineral density. Such lines might be thought of as a "first generation" of nutritionally improved varieties. Other generations will follow as more is learned about reducing levels of compounds that inhibit bioavailability and increase absorption, and as new genes are added through biotechnology.

The conclusion is that, among other strategies, there is a niche for plant breeding and for reducing the population prevalence of IDA at the lowest cost. If this strategy proves to be inexpensive and cost-effective by improving plant nutrition and increasing yields, it will complement but not in any way substitute for supplements or fortification, which are equally important. The potential that biotechnology offers for enrichment of cereals is described briefly in Appendix 2. A considered view is that the agricultural-industrial partnership becomes all the more critical in the coming years as one sees the explosion of urban populations and therefore urban children in Asia, to about 2.5 billion people by 2025, increasing dependence on food-based solutions to both Green Revolutions.

Building a regional investment partnership for poor Asian women and children

From an investment perspective, a major regional effort in Asia to shift public resources toward public-private partnership will promote fortification of staples and complementary foods for infants, and recast the goals of the seed industry to meet human nutrition goals including the IDG. This obviously deserves extensive discussion. Our task is to disseminate to policymakers information about what the status quo costs in lives, disabilities and lost resources, and how beneficial fortification and plant breeding approaches could be applied. The donor and professional communities should then provide concerted support.

More attention must be turned to linking food fortification and seed technology in the public interest. One example of a diversified strategy is being carried out by the Asian Development Bank with a broad spectrum of partners in the donor community throughout Asia (Appendix 3).

In conclusion, there is no question that the time has arrived to eliminate both iron deficiency and poor child growth in Asia, because the problems are interlinked and the food-based solutions are at the cutting edge of current science and technology. The opportunity for a greater scope for the private sector to have its effect is well described (23,27). It is now simply a matter of gathering the political will to realize the achievable. All interventions, whether supplementation, fortification or plant breeding must pass three tests: efficacy, effectiveness and cost effectiveness. Iron nutrition is on the threshold of economic policy, but not yet at the center; we should ask ourselves why and correct the situation. Research and advocacy are really not linked, but can be, supported by more detailed economic analysis for each intervention. New priorities are to look at the cost effectiveness of key integrated strategies, particularly joint reduction of maternal anemia and low birth weight, infant care that combines breast feeding and complementary feeding, and the agricultural industrial partnership for iron enrichment of poor women and children.

APPENDIX 1: Benefit Cost Analysis of Biofortification

The two fundamental reasons to expect high payoffs to investments in breeding for iron and zinc dense seeds of food staple are as follows: *1*) fixed costs of research at a central location may accrue across countries and over time at low recurrent costs; and *2*) not only are there nutritional benefits, but agricultural productivity may be increased as well. This may be demonstrated empirically with a simple benefit cost calculation for India and Bangladesh, where the two major staples eaten are rice and wheat (total population of 1.125 billion; 55 million hectares (ha) of rice and 28 million ha of wheat harvested annually).

Fixed costs. For any single staple crop, the estimated central fixed costs over 10 y of developing iron and zinc dense rice varieties are estimated to be \$12.5 million. This figure includes several costs not directly related to breeding such as for nutritional studies to establish efficacy and to demonstrate effect after adoption. Conservatively, assume that all of these central, fixed costs are charged to India and Bangladesh. It is further assumed that \$2.5 million per crop is spent on adaptive breeding specifically for growing conditions in India and Bangladesh, again over the same 10-y period.

Variable costs. Various rates of adoption of nutritious varieties are assumed in the simulations and extension costs are tied to the rates of adoption, specifically \$1/adopted ha. Thus, if adoption occurs on 10% of rice and wheat area (8.3 million ha), then a fixed undiscounted extension cost of \$8.3 million is incurred. Varieties are assumed to come on line gradually after y 10 of the simulation, for example, in a 10% adoption scenario, to cover 2% of total area in y 11, 4% in y 12, 6% in y 13, 8% in y 14, and 10% of total area in all years thereafter. Recurrent costs (such as for maintenance breeding) of \$500,000 annually are assumed after the initial 10-y period of fixed investments. Thus, in a 25-y simulation, assuming a 10% adoption rate, \$42 million in undiscounted costs may be incurred in total.

Nutritional benefits. Nutritional benefits are tied to assumed rates in reduction of anemia. Using an analysis (28) that provides empirical estimates of the relationship between hemoglobin levels of rural Bangladeshi women and their intakes of iron and other nutrients and compounds, it is conservatively estimated that anemia prevalence rates would be reduced by 3% by those consuming the nutritious rice and wheat (e.g., a reduction of 3% of 10% of the population under a 10% adoption scenario, or 3.375 million cases of anemia averted each year). This is a conservative estimate for several reasons: *1*) the assumed increase in iron due to breeding is based on current, limited knowledge of what can be expected from conventional breeding; new breakthroughs, e.g., using biotechnology, are likely; *2*) because of measurement error from a number of sources, regression estimates in the study (28) can be expected to underestimate the true relation between improvements in diet and improved iron status; *3*) no nutritional benefits are assumed for increased zinc intakes or for those whose iron intakes increase but who remain anemic (50 million people under a 10% adoption scenario; 45% of 10% of the population). Benefits to cases of anemia averted are those estimated by Horton and Ross (26) for India and Bangladesh, a discounted present lifetime value of \$27.50/case.

Benefit/Cost relationships. Even these conservative assumptions concerning nutrition benefits will justify the investment cost (as shown in **Table 2**). In addition, increased seed zinc density may increase rice and wheat yields substantially and lower seeding rates (29). Yield increases of 250 kg (8% on a base yield of 3 t/ha) of unmilled rice and wheat are assumed on adopted areas, giving a net incremental undiscounted profit of ~\$35/(ha · y).

Even though all centralized, fixed costs of \$25 million are charged to India and Bangladesh, Table 2 suggests that nutritious varieties may reach undernourished populations at a cost of only \$0.02–0.03/(person · y). Depending on adoption rates and the levels of iron that can be added to food staples through breeding, anemia may be averted for as little as \$0.22–0.36/case. Internal rates of return on nutrition benefits should be well above 25%. If agricultural benefits are also considered, several billions of dollars of benefits can be expected on investments of tens of millions of dollars.

APPENDIX 2: Biotechnology: Untapped Potential for Iron Enrichment of Rice

The prospects for biotechnology are quite exciting in four respects, and may eventually surpass the effect of conventional plant breeding (30,31).

Increasing iron content. Goto et al. (32) reported improving the iron content of rice by transferring the entire coding sequence of the soybean ferritin gene into a Japonica rice. The transgenic seeds stored up to three times more iron than the normal seeds. Potrykus and colleagues at the Swiss Federal Institute of Technology (SFIT) have announced a doubling of the iron content in rice using a ferritin gene from *Phaseolus vulgare*.

Increasing promoters. Datta (33) has increased levels of lysine, a limiting amino acid that might promote the uptake of trace minerals, by genetic engineering. Other biotechnology work on canola and soybean seeds has increased lysine content fivefold (34).

Introducing a heat-stable phytase gene, which breaks down phytic acid. The phytase level in rice is generally low. However, the SFIT team has reported introducing a transgene for a heat-stable phytase from *Aspergillus fumigatus*, which increased the level of phytase 130-fold. This opens new possibilities for neutralizing antinutrients in cereals.

Adding β-carotene. β-Carotene, a precursor of vitamin A (retinol), does not occur naturally in the endosperm of rice. But Ye et al. (35) have reported generating a large series of transgenic plants that produce grain with yellow-colored endosperm at significant density levels. This bears watching, although consumer acceptance may be a concern. β-Carotene is an important promoter of iron absorption.

Certain approaches to nutritional improvement of grains, including the introduction of β-carotene and heat-stable phytase genes, offer clear advantages to biotechnology because these approaches are not feasible using conventional plant breeding. However, biotechnology breeding strategies must be demonstrated to be superior to other methods, beginning with rice. Biotechnology methods must be subjected to stringent

TABLE 2

Developing iron and zinc dense rice for India and Bangladesh: simulated benefits and costs over 25 years[1]

	Variety adoption rate					
	10%			20%		
	Anemia reduction rate					
Description of benefits and costs	3%	4%	8%	3%	4%	8%
Cost per person reached who consumes nutritious staples (undiscounted)	0.03	0.03	0.03	0.02	0.02	0.02
Cost per case of anemia avoided (undiscounted)	0.96	0.72	0.36	0.58	0.44	0.22
Internal rate of return on nutrition benefit	28.9%	31.8%	39.2%	34.0%	37.1%	44.9%
Total investment for research and extension ($million undiscounted)	42.1	42.1	42.1	51.2	51.2	51.2
Total nutrition benefits (3% discount rate; $million)	694.2	925.6	1851.2	1388.4	1851.2	3702.4
Total agricultural benefits (3% discount rate; $million)	2142.7	2142.7	2142.7	4285.3	4285.3	4285.3
Total benefits (3% discount rate; $million)	2836.9	3068.3	3933.9	5673.7	6136.5	7987.7
Total costs (3% discount rate; $million)	35.9	35.9	35.9	43.7	43.7	43.7
Ratio nutrition benefits/total costs	19.3	25.8	51.5	31.8	42.4	84.7

1 Source: H. Bouis, International Food Policy Research Institute, Washington, DC (2001), private communication.

tests regarding agronomic effects, organoleptic properties and consumer acceptance, health and environmental effects, and control of intellectual property rights. But cautious optimism is warranted that breakthroughs are imminent.

APPENDIX 3: Asian Development Bank (ADB) Strategies to Eliminate IDA

Asia's ability to reduce the alarmingly high rates of maternal mortality and cognitive impairment in children depends substantially on major efforts to reduce IDA. A clear strategy is urgently required to reduce IDA among women of reproductive age or young children. Their respective risks are death during pregnancy and impaired physical and cognitive development, expressed as delayed speech and reading skills, which adversely affect school achievement. A substantial proportion of the 500,000 maternal deaths in developing countries are caused by severe IDA (3,4).

Regional initiatives. ADB is supporting three regional initiatives that focus on the public and private sectors cooperating to solve the problem of IDA. Regional studies on food fortification and rice plant breeding are ongoing, with the expectation that, by 2003, ADB will lead major initiatives in the region to raise the iron density of essential staples consumed by the poor at affordable prices. A subregional initiative in the Trans-Caucasus Central Asia (TCAA) will help six countries fortify flour and salt through integrated attention to production, regulation and trade.

Essential foods fortification. The regional food fortification project cosponsored by International Life Sciences Institute and Government of Denmark (36) focuses on the iron fortification of wheat flour, *iron-enriched complementary foods for infants*, and condiments such as soy sauce and fish sauce, all widely consumed by the poor in the region. People's Republic of China, India, Indonesia, Pakistan, Thailand and Viet Nam are participating in the project. Iron fortification emerged as a regional priority at a regional strategy meeting hosted by the ADB in February 2000 (36). Prominent government food regulators and captains of Asian food industries pledged to cooperate in reducing micronutrient malnutrition in the region. IDA was identified as the top priority for concerted action. The project will develop a regional investment plan based on country studies, and regional workshops on food technology, regulation and trade.

Rice plant breeding. The second regional strategy is rice plant breeding through a donor consortium led by ADB (37). A 3-y research study ending in 2003 will test promising rice varieties with high iron and zinc density to ensure that their yield is adequate, that the iron and zinc are bioavailable to consumers, that consumers are willing to eat the varieties, that the production and dissemination of the new varieties is feasible for national agricultural research systems and seed companies and that the rice will be affordable to the poor.

Flour and salt fortification. The third regional activity, supported by the Japan Fund for Poverty Reduction (38) responds to the breakdown in production of fortified flour and salt in the TCCA subregion. The project aims to set up production systems and build capacity for improved regulation, quality control and trade of fortified flour and salt, so that poor women and their children will obtain adequate iron and iodine through daily consumption of these staples.

ACKNOWLEDGMENT

The author is grateful to Howarth Bouis for contributing a technical note (Appendix 1 of the paper) on the benefits and costs of the plant breeding strategy for iron enrichment of cereals. Bouis is a senior research scholar at the International Food Policy Research Institute, Washington, DC and a leading thinker on the role of agricultural research in improving human nutrition.

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