

Economic Impact Analysis of Marker-Assisted Breeding in Rice

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Conventional rice breeding typically requires 10-15 years from initiation to varietal release. Abiotic stresses in rice, such as salinity and phosphorous deficient soils, cause significant losses, especially in marginal areas, and can be difficult problems to solve through conventional breeding because of “genetic load” or undesirable traits that accompany desirable ones during backcrossing. Soil amendments of affected soils are an expensive alternative and impractical for poor farmers who often farm in these areas. Scientists have turned to marker-assisted breeding (MAB) to develop rice varieties with tolerance to salinity and P-deficiency. DNA molecular markers for these traits are available and molecular rice breeders are in a position to use MAB to selectively incorporate quantitative trait loci¹ (QTL)/genes into existing rice varieties in Asia. In principle, conventional backcrossing could be used to incorporate the traits. However, MAB, enabled by advances in genomics and molecular mapping in recent years, is potentially more precise (less genetic load), time-saving, and cost-effective. Through these modern molecular tools, the genetic basis of tolerance can be unraveled, and tolerance genes can be tagged and traced in the breeding process.

Surprisingly little economic analysis has been undertaken to assess the potential impacts of MAB, even for a major crop such as rice. If the breeding process can be reduced by a just few years, the potential gains are significant, with many of the benefits going to the poorest farmers. Production would increase on unfavorable lands and additional areas might be brought into production. Higher production would translate into

¹ Quantitative trait loci (QTL) are the regions within genomes that contain genes associated with a particular quantitative trait (Collard et al. 2005).

larger profits and poverty alleviation. However, molecular breeding also requires resources, and effort spent targeting traits for marginal rice lands may be effort diverted from breeding for favorable rice environments. Therefore, economic impact analysis is needed to assist in designing an optimal breeding portfolio.

The purpose of this paper is to report on an ex ante economic impact assessment of marker assisted selection in rice to: (a) provide early estimates of benefits of the initial investment in developing and applying these markers², and (b) validate an approach to impact assessment that might be employed for other projects, especially those funded by the Generation Challenge Program (GCP) of the CGIAR³, to document progress and to assist with future prioritization of research resources. The goal is to provide an assessment that is detailed enough to generate credible evidence of impact, yet simple enough to facilitate use of the evaluation methods more broadly for other marker-assisted-selection projects of the GCP.

Economic benefits in this study are projected based on the situation with and without the MAB technologies. Benefits are calculated over 20 years for Bangladesh, India, Indonesia, and the Philippines, taking into account (a) rice areas currently affected by the target stresses, projected changes in these areas, and rice production in these areas, (b) the nature of the markets for the crops, (c) the projected yield and cost changes due to the new technologies, (d) the estimated time for discovery, development, and deployment of the marker technologies and associated germplasm, (e) the estimated time required to

² This investment is through a rice project entitled: “Revitalizing marginal lands: discovery of genes for tolerance to saline and phosphorus deficient soils to enhance and sustain productivity, ” led by the International Rice Research Institute (IRRI) in the Philippines.

³ The CGIAR is the Consultative Group for International Agricultural Research.

breed, test and disseminate superior new cultivars, including the rate of adoption by farmers, and (f) the discount rate for benefits and costs that occur over time.

This paper begins with a brief description of the biological research being undertaken on the GCP rice project, describing the pathway through which the technology is developed and eventually reaches producers. Describing this pathway is a first step in identifying (a) the relationship between the MAB rice research and other research, (b) the likely outputs from the GCP project, and (c) how project outputs will likely be staged over time and in different geographic areas. The second step is to gather data on rice production, prices, and trade. The third is to identify existing crop losses due to salinity and P-deficiency and what would be done to manage these stresses without the project. The fourth step is to construct budgets of input costs with and without the technology. The fifth is to assess market-level income effects using economic surplus analysis, combining information on production, prices, markets, yields, costs, research, dissemination, and adoption lags. Finally, the benefits (economic surplus) and research costs are combined in a benefit costs analysis to calculate net present value and rate of return on investment.

Technology Impact Pathway

The rice MAB rice project contains two parallel research thrusts. Before the project began, QTLs were found for salinity (named *Saltol*) and P-deficiency (named *Pup1*) tolerance. The first thrust of the project was then to identify genes associated with the *Saltol* and *Pup1* loci through “fine mapping” of the QTL. A second thrust was to develop a marker system to incorporate these genes into popular varieties. The project has been

led by the International Rice Research Institute (IRRI), but is linked to national agricultural research and extension systems (NARES) in Asia, both for capacity building in MAB and for incorporating the genes into popular varieties.

The purpose of fine mapping of the QTL is to reduce chances that the new lines do not contain the targeted traits. The finer the mapping, the greater the certainty that the gene is present, and therefore the smaller the part of the chromosome they have to take and the smaller the risk of unwanted traits. Once the gene is found (or small set of 2-5 genes) other sources of tolerance can be sought to combine with it. The *Saltol* and *Pup1* loci have been narrowed down to about 150 genes, and then marker assisted backcrossing began while fine mapping continued. With a conventional breeding system, backcrossing would take about 10 years, but with MAS this time is reduced by about 3 years.

Relationships among past, current, and future research on salt and P-deficiency tolerance are summarized in figure 1. Past research achievements, including work on submergence tolerance, paved the way for the current project on salt tolerance and P-deficiency tolerance. Current research also builds on fundamental research developing DNA markers and sequencing the full rice genome. Future research activities will include gene pyramiding of additional traits and incorporating salt-tolerance during the reproductive stage of rice.

In 1993, IRRI developed IR66946, a cross between two *indica* rice varieties: the salt-tolerant traditional variety Pokkali and the elite but salt-susceptible IR29. Since then, traditional rice lines with high levels of salt tolerance have been used in conventional backcrossing programs to develop high-yielding salt-tolerant elite varieties (Ismail et al., 2007). However additional salt tolerance is needed and a drawback with conventional

backcrossing is the length of time to develop a new variety. Six to eight backcrosses are typically needed, which translates to approximately 3-4 years (1 generation = 1 season of planting; 1 year = 2 backcross generations) of breeding work. There is no absolute number for how many backcrosses are needed (Collard and Mackill, 2008), and sometimes it can take 10-15 years to develop a variety.

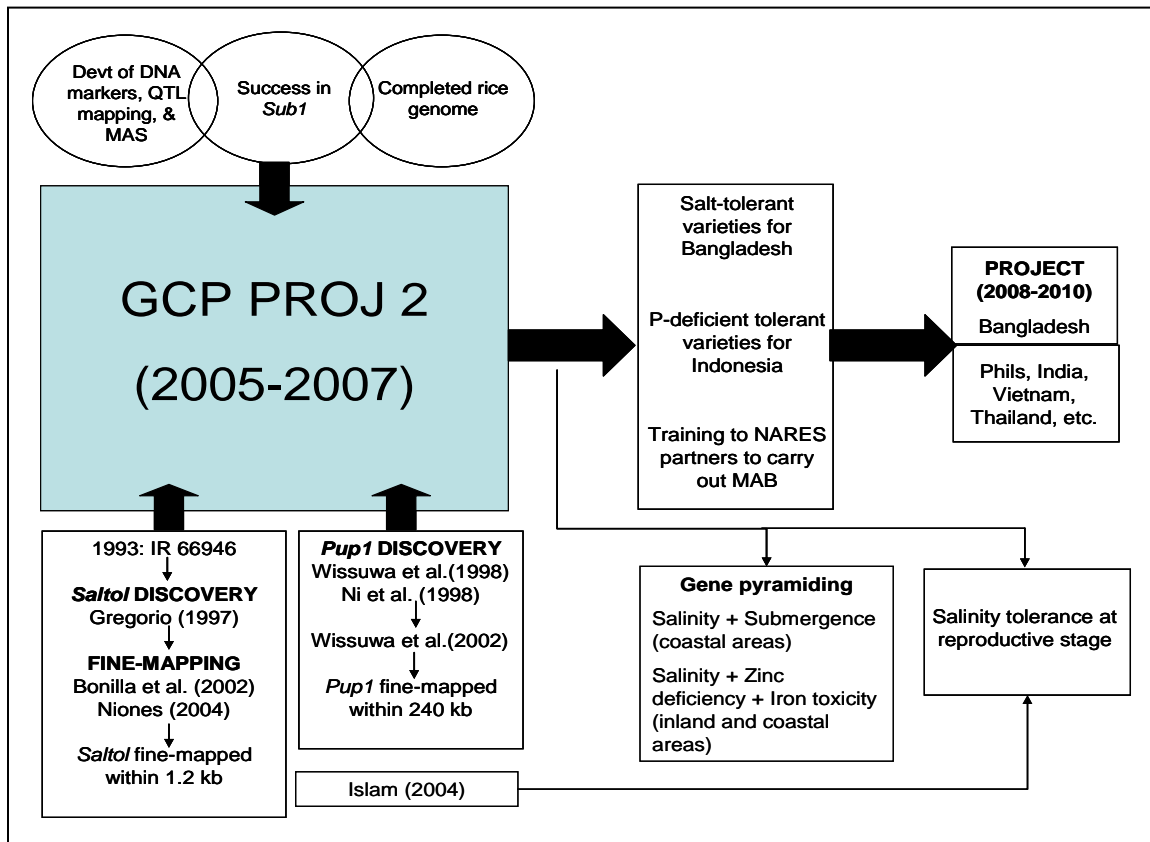


Figure 1. Research linkages among past, current, and future research related to molecular breeding for salt and P-deficiency tolerance.

Another obstacle with conventional breeding is the genetic load (also called “linkage drag”) mentioned above, wherein undesirable genes included in the chromosomal region where the target gene is located are brought along when the target

gene is transferred into the popular variety. These unwanted genes from the donor parent might negatively affect the performance of the popular variety. Linkage drag requires many additional backcross generations, and if the undesirable genes are really tightly linked to the target locus it may be difficult to eliminate these genes using conventional backcrossing (Collard and Mackill, 2008).

The breeding efforts to develop salt-tolerant rice varieties are also constrained by the complexity and polygenic (multi-gene) nature of the salt tolerance trait (Singh et al. forthcoming). Unlike the *Sub1*, which is a single gene, salinity tolerance is a quantitative trait controlled by many genes. Hence, accurate phenotypic identification of salt tolerant lines is difficult because it is heavily affected by environmental variation that prevents visible expression of the trait. Being governed by two or more genes that significantly interact with the environment means that heritability of salt tolerance is a low 19.18% (Islam 2004). Consequently, tolerance of the breeding lines is not as high as that of the traditional donor parents such as Pokkali (Ismail et al. forthcoming). Selection for salinity-tolerant genotypes of rice based on phenotypic merits alone is less reliable and delays breeding progress (Islam 2004).

Fortunately, advancement in genomics, development of markers, and molecular mapping have provided tools for molecular identification of complex traits such as salinity tolerance. Molecular markers are used for linkage mapping of stress-tolerant genes/QTLs, which can then be transferred into popular varieties (Singh et al. forthcoming). These developments gave rise to marker-aided breeding which allows efficient selection and quicker variety release.

The mapping program for salinity tolerance at IRRI was initiated by Gregorio (1997). He was able to map a common *Saltol* QTL for salinity tolerance. His research prompted other studies (Bonilla et al., 2002; Niones, 2004) to fine map the *Saltol* QTL to identify the precise location of *Saltol* on chromosome 1. For phosphorus deficiency, Wissuwa et al. (1998) and Ni et al. (1998) detected the major QTL *Pup1* on chromosome 12, which improves the plant's uptake and capability to extract a higher proportion of fixed P in the soils. Physiological studies suggest that the *Pup1* gene is expressed in root tissue where it either leads to higher root growth per unit P (higher internal efficiency) or improves P uptake per unit root size (external efficiency) (Wissuwa 2003). In summary, the GCP project benefited from the excellent progress made in understanding the physiology of salinity and P deficiency tolerance, and in the earlier efforts of fine-mapping *Saltol* and *Pup1*.

The GCP project at IRRI is incorporating *Saltol* into at least one Aman (wet) season and one Boro (dry) season variety already popular with farmers in Bangladesh. It is also incorporating *Pup1* into at least two popular upland varieties in Indonesia. The project also is developing a marker system to incorporate QTLs/genes into popular varieties through MAB. This system is needed because several varieties are specific to each country and it would be difficult for the project itself to develop multiple varieties for every country on the project. By developing markers which are optimized for specific varieties and tested for compatibility with recurrent parents, and transferring the marker system to partners in national agricultural research and extension systems (NARES), local scientists can conduct the MAB themselves, and incorporate the tolerance traits to whatever variety they prefer. Hence, the MAB package, which includes the markers

(foreground, flanking, and background) and the donor parents (i.e. IR64*Saltol*), are being transferred to NARES in the target countries. The markers are already optimized and tested for compatibility for specific popular local varieties (recurrent parent) enabling these local institutions to save resources. The breeding work will be shortened since scientists do not need to develop a new variety from scratch. Moreover, because the original popular variety is maintained, there should be a high rate of farmer adoption. Another component of the project is to train scientists through degree and non-degree programs so that they can successfully incorporate the tolerant genes into their local varieties.

A major requirement before approval and release in farmer's fields is testing the varieties via experiment stations and on-farm trials. In fact, a new project is being initiated to test and validate BR28 with NARES and to bring the variety to farmers' fields in Bangladesh. The project is expected to run for 3 years (2008-2010). This endeavor is also expected to serve as example and motivation for the development and release of the improved varieties in India, Philippines, and other rice growing countries.

A summary of the technology pathway from research just prior to the MAB project to eventual release of improved varieties to farmers is provided in Table 1. The entire molecular breeding program takes about 10 years. In contrast, an outline of this same set of steps for conventional breeding would take 4-6 years longer due to the need for multiple backcrosses in step 3.

Table 1. Summary of Impact Assessment Pathway for Discovery of Genes for Tolerance to Salinity and P-Deficiency

| Steps in the research and breeding process | Time (years) |
|--|---------------------|
| 1. Work prior to GCP project – Identified course mapping of salinity gene and P-deficiency gene. | |
| 2. GCP project fine mapped the traits down to less than 150 genes (there might be more than one gene involved). | 1.5 |
| 3. Began marker-assisted backcrossing when fine mapped to 150 genes. Developing new varieties through this system. | 2.5-3.0 |
| 4. Testing and validating of these new varieties before sending to NARES to test and validate | .5 |
| 5. Test and validate in NARES, at least 1 season on station and 1 season in farmers' fields. | 2.0 |
| 6. Release and scale up seeds in Bangladesh for salinity and Indonesia for P | 3-4 |
| 7. Total time | 9.5-11 |

A second technology pathway starts from the point where the markers themselves along with the donor variety are transferred to the NARES so the NARES can undertake a new set of marker-assisted backcrosses to incorporate the tolerance genes into additional varieties. Once the location of the QTL/gene is precisely identified, it can be transferred to any variety. The use of markers replaces pheno-typing (selection based on visible characteristics), allowing selection in the off-season which increases generations per year, and reducing the number of breeding lines that need to be tested for undesirable traits.

Rice production, prices, and Trade

Rice supplies more than 30 percent of total calories consumed in Asia, and Asia accounts for almost 90 percent of the world's rice production and consumption. The poor produce

rice disproportionately in unfavorable eco-systems, including upland areas with poor soils and irrigated areas with salinity problems. Among the countries targeted by the GCP project, India is by far the largest rice producer but each country is a major rice producer and consumer (Table 2).

Table 2. Rice production (1000 tons) in the Project Countries

| Year | Philippines | Bangladesh | India | Indonesia |
|-------------|--------------------|-------------------|--------------|------------------|
| 2002 | 13,271 | 37,593 | 107,730 | 51,490 |
| 2003 | 13,500 | 38,361 | 132,739 | 52,138 |
| 2004 | 14,497 | 36,236 | 124,698 | 54,088 |
| 2005 | 14,603 | 39,796 | 137,620 | 53,985 |
| mean | 13,967.75 | 37,996.5 | 125,696.75 | 52,925.25 |

Source: FAO core production data (<http://faostat.fao.org>)

The mean rice price by country is provided in Table 3. Average rice price ranged from \$126 per ton in Bangladesh to \$173 in the Philippines. Rice prices in the past few months have gone significantly higher, and therefore our base results which utilize these average prices may under estimate benefits of the technologies.

Table 3. Rice price (US\$/ton) in the Project Countries

| Year | Philippines | Bangladesh | India | Indonesia |
|-------------|--------------------|-------------------|--------------|------------------|
| 2002 | 171 | 114 | 124 | 134 |
| 2003 | 163 | 103 | 134 | 140 |
| 2004 | 169 | 143 | 142 | 176 |
| 2005 | 189 | 144 | 150 | 210 |
| mean | 173 | 126 | 137.5 | 165 |

Source: FAO core production data (<http://faostat.fao.org>)

Bangladesh, Indonesia, and the Philippines are rice importing countries with 3%, 5%, and 6% of the world market, respectively. India is a relatively large rice exporting country, with 21 % of world exports.

Salinity and Phosphorus Deficiency

The extent of salinity-affected areas where rice is or might be grown is indicated in Table 4. Saline rice fields occupy 5%, 7%, 3%, and 4% of total rice area in the Philippines, Bangladesh, India, and Indonesia, respectively. Though these are relatively low percentages, the yield increase in these areas could increase rice production significantly, especially for subsistence farmers.

Rice saline areas also include severely affected lands that are left uncultivated currently, but which could be reclaimed by planting the tolerant varieties. There are no reliable data on the magnitude of these areas, but they are assumed to represent about 10% of the total saline land where rice could be grown.

Table 4. Extent of salinity affected areas where rice is or might be grown (000 ha)

| Country | Saline Rice Area ¹ | Total Saline Agricultural Land ² | Total Rice Area ³ | Percent of Total Rice Area That is Saline |
|-------------|-------------------------------|---|------------------------------|---|
| Philippines | 200 | 500 | 4047 | 5 |
| Bangladesh | 800 | 2400 | 10,738 | 7 |
| India | 1500 | 6600 | 43,135 | 3 |
| Indonesia | 500 | 1000 | 11,669 | 4 |

1. Source: Interviews with IRRI rice scientists
2. Source: FAO <http://www.fao.org/ag/agl/agll/spush/topic2.htm>
3. Source : IRRI WRS <http://www.irri.org/science/ricestat/>

There are 2 types of salinity. The first is caused by salt water intrusion along the coast. The second is which is human-induced salinity caused by irrigation mismanagement (including insufficient water application, irrigation at low efficiency, seepage from canals and water losses on the farm, and irrigation with saline water or marginal quality water without soil and water management), poor land leveling, dry season fallow practices in the presence of shallow water table, misuse of heavy machinery and soil compaction, excessive leaching with insufficient drainage, and use of improper cropping patterns and rotations (FAO). In addition to FAO, there are other studies that estimate the extent of salinity in the project countries, but the estimates presented in Table 4 appear to be reasonable in sense of falling within the ranges indicated in those studies. There is also seasonal variation in salinity, with salinity higher in the dry season (Ismail et al. forthcoming). In some instances, severe salinity and lack of irrigation can leave lands uncultivated during dry season. These are the fallow lands that scientists feel can be brought into production once the saline tolerant varieties are made available to farmers.

Rice with salinity tolerance is expected to increase yield in affected areas by 0.5 to 1 ton/ha (Mahabub Hossain, IRRI, personal communication). FAO reported that in severe cases of salinity in the Philippines, farmers currently harvest 1.5 to 2.5 tons/ha. In Bangladesh, rice yields in salt-affected areas average 1.0 to 1.6 tons/ha (Islam and Norton, 2007). In India, Siddiq (2000) reports an average yield of 2.10 tons/ha in saline areas. No data were found for Indonesia, but a yield of 2 tons/ha is assumed. Overall, it is assumed that saline-tolerant varieties would increase yields in affected areas by 50%, 60%, 48%, and 40% in the Philippines, Bangladesh, India, and Indonesia, respectively.

P-deficiency is primarily a problem in upland areas, which in Indonesia represent about 9 percent of the total rice area or one million ha (Syaukat and Pandey). It is assumed that all of that one million ha of upland rice suffers from P deficiency, as the soils are highly weathered, acidic, and inherently low in P. Upland soils have high capacity to fix P in forms not easily available to crops, and hence are inherently low in P (IRRI 1996; Lafitte, Ismail, and Bennett; Wissuwa 2003). Most of the rice farms in upland areas are small subsistence farms that use little or no purchased inputs (Sacks et al. 1999).

IRRI indicates an average yield of about 1 ton/ha in upland rice areas of Asia, but in Indonesia it is closer to 2 tons. With tolerance to P-deficiency, it is estimated that yield will increase by 1 ton/ha in upland areas or about a 50% increase. This relatively significant yield effect is assumed because experiments show that rice with *Pup1* extracts up to 3 times as much naturally occurring soil phosphorus (Wissuwa and Ae, 2001).

Changes in Costs

Input cost data for the Philippines, Bangladesh, and India were obtained from the Philippines Rice Research Institute (PhilRice), Islam and Norton (2007), and an IRRI-ICAR-NDUAT Collaborative Research Project report, respectively and were used to calculate input cost shares. The Philippine shares were also used in Indonesia. The input cost shares are shown in Table 5, along with the estimated proportionate change in cost per hectare associated with the salinity tolerant variety. The latter were obtained from IRRI scientists. Multiplying costs shares by the proportional costs changes and totaling

gives proportionate costs changes of 0.05 to 0.07 per country with most of the change due to added labor cost associated with harvest labor.

Table 5. Current input cost shares and proportional cost changes per hectare for saline-tolerant rice

| Input | Cost shares | | | | Proportionate Cost Change |
|----------------------|-------------|------------|-------|-----------|---------------------------|
| | Philippines | Bangladesh | India | Indonesia | |
| Seed | .03 | .07 | .04 | .03 | 0.0 |
| Fertilizer | .09 | .14 | .21 | .09 | .05 |
| Pesticide | .05 | .03 | .01 | .05 | .05 |
| Labor | .42 | .53 | .51 | .42 | .10 |
| Machine/tools/animal | .10 | .12 | .16 | .10 | .05 |
| Irrigation | .05 | .11 | .07 | .05 | 0.0 |
| Other | .28 | 0.0 | 0.0 | .28 | 0.0 |

For P-deficient tolerant varieties, no increases or decreases in seed, fertilizer, pesticide, or irrigation costs are projected. Additional costs are expected to be incurred from machinery (5%) and labor (10%) for harvest. Machinery costs are originally 9% and labor costs 57%. Similar to the assumption for saline-tolerant rice, there would be no change in cost of irrigation and other inputs. The overall proportional input cost change per ha for Indonesia for the P-deficient tolerant varieties is 0.06.

Technology Adoption and Economic Surplus Analysis

Cost and yield changes can be combined with projected varietal adoption rates in an economic surplus analysis to calculate income changes associated with the new technologies. It is projected that salinity-tolerant varieties will be released in 2014 in Bangladesh and in 2015 in India. In the Philippines and Indonesia where the NARES themselves do additional breeding work, the varieties are released in 2017. It is projected that a P-deficiency tolerant variety will be released in Indonesia in 2014. It is projected that farmer adoption will then take six years to reach maximum adoption of 50% of the rice areas subject to salinity or P-deficiency. The maximum adoption is projected to remain the same for five years and then adoption will decline for five years as the varieties are gradually replaced.

Rice markets for Bangladesh, Indonesia, and the Philippines can be represented as small open economies given that they are small importers in the world market. In this case, price remains constant and benefits from the technology-induced supply shift accrue to producers. The rice market for India is best represented as a large open economy, given the size of its exports in the world market. Graphical descriptions of the economic surplus changes associated with farmer adoption of the improved varieties are presented in Figure 1 and Figure 2 below. For the large open economy case, both producers and consumers in India potentially benefit from the technology. The basic assumptions incorporated in the economic surplus models for salinity and P-deficiency tolerance in the target countries are summarized in table 6. All of the assumptions and economic surplus formulas were incorporated in spreadsheets to complete the economic surplus calculations.

Table 6. Summary of key parameters used in economic surplus models

| Parameter | Bangladesh | India | Philippines | Indonesia Salinity | Indonesia P-deficiency |
|---|-------------------|--------------|--------------------|-------------------------------|-----------------------------------|
| Year of release (after seed multiplication) | 2014 | 2015 | 2017 | 2017 | 2014 |
| Year of release if conventional breeding | 2017 | 2017 | 2021 | 2021 | 2017 |
| Max. % adopt. Rate | 50 | 50 | 50 | 50 | 50 |
| Supply Elasticity | .13 | .10 | .40 | .32 | .32 |
| Demand Elasticity | -.29 | -.25 | -.58 | -.48 | -.48 |
| Yield change (%) | 74 | 48 | 50 | 50 | 50 |
| Cost change (%) | 7 | 7 | 5 | 5 | 6 |
| % rice area affected | 7 | 3 | 5 | 4 | 9 |
| Base price (\$/MT) | 122 | 135 | 174 | 150 | 150 |
| Base quantity (1000 tons) | 37,647 | 128,356 | 13,536 | 52,343 | 52,343 |

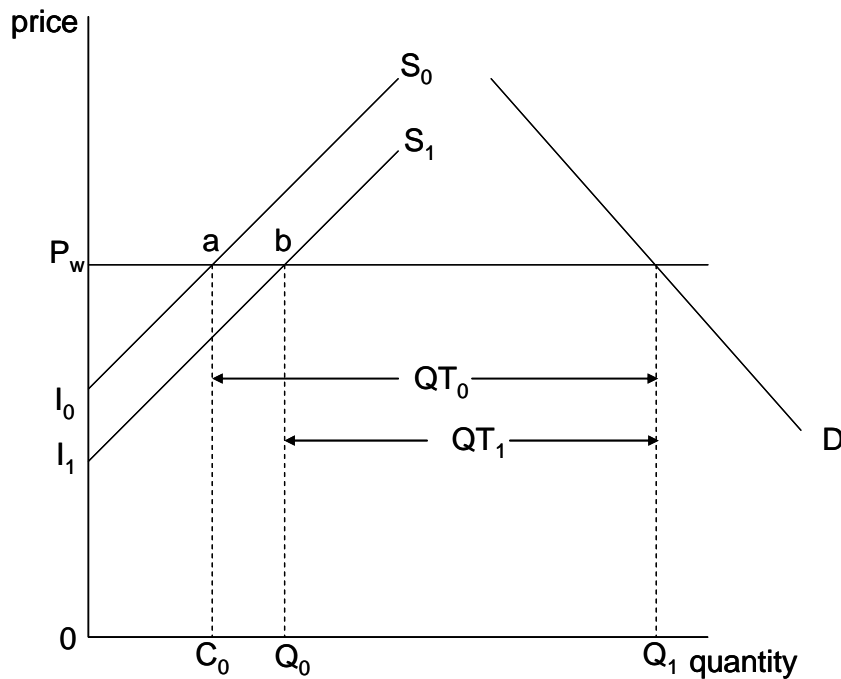
The small open economy model is presented in Figure 1. The initial equilibrium is at consumption of C_0 , production of Q_0 , and import price of P_w . Net imports equal QT_0 . With the new technology, production increases and the supply curve shifts from S_0 to S_1 . This leads to a decrease in imports to QT_1 . And since the country does not affect P_w , the economic surplus change of area I_0abI_1 is all producer surplus (PS). The gain in PS can be represented algebraically as: $\Delta PS = \Delta TS = P_w Q_0 K(1+0.5K\varepsilon)$, where P_w is world price, Q_0 is pre-research quantity, K is the proportionate cost reduction per ton due to the technology, and ε is the supply elasticity. K is calculated using the following formula:

$$K = \left(\frac{E(Y)}{\varepsilon} \right) - \left(\frac{E(C)}{1 + E(Y)} \right) p A_t (1 - d_t),$$

where $E(Y)$ is the expected proportionate yield

increase per hectare after adoption of the new technology, $E(C)$ is the expected proportionate increase in variable input cost per hectare, p is the probability of success with the research, A_t is the adoption rate for the technology in time t , and d_t is the depreciation rate of the new technology.

Figure 1. Small open economy economic surplus model



Source: Figure 4.5 of Alston et al. (1995)

When the innovating country is a “large country” in trade such as the case with rice in India, it can influence the international price of the commodity. The world market is modeled in terms of trade between the home country (country A) and ROW so that market clearing is enforced by equating excess supply and excess demand. The supply

and demand in country A is represented in panel a, and panel c illustrates the aggregated supply and demand in the ROW.

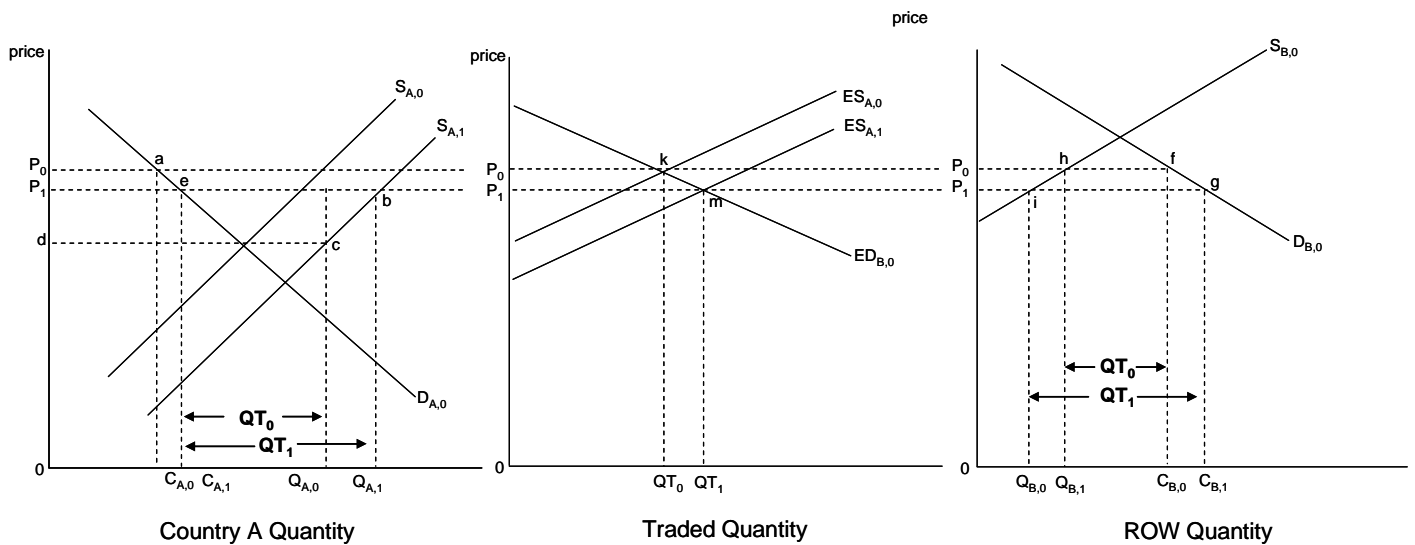
The following description is based on Alston et al. (1995), (p.214-216). ES_0 is the excess (export) supply in country A, which is the horizontal difference between the domestic supply (initially $S_{A,0}$) and demand (initially $D_{A,0}$). The initial excess (or import) demand from ROW is shown as $ED_{B,0}$ and is given by horizontal difference between the ROW demand (initially $D_{B,0}$) and supply (initially $S_{B,0}$). International market equilibrium is established by the intersection of excess supply and demand at a price P_0 . The corresponding domestic quantities are shown as consumption ($C_{A,0}$), production ($Q_{A,0}$), and exports (QT_0). The ROW consumption, production, and imports are represented as $C_{B,0}$, $Q_{B,0}$, and $Q_{T,0}$, respectively. With the adoption of technology in the home country, domestic supply shifts from $S_{A,0}$ to $S_{A,1}$, and consequently, the excess supply shifts from $ES_{A,0}$ to $ES_{A,1}$. P_1 then becomes the new equilibrium price, and the new corresponding domestic quantities are $C_{A,1}$ for consumption, $Q_{A,1}$ for production, and $Q_{T,1}$ for exports. The ROW quantities, on the other hand, are shown as consumption, $C_{B,1}$, production, $Q_{B,1}$, and imports, QT_1 .

The reduction in P_w , caused by the research-induced supply shift, helps consumers in both countries and producers in country A, but affects ROW producers negatively. In panel a, the area P_0aeP_1 behind the demand curve and area P_1bcd behind the supply curve represents the domestic consumer and producer benefits, respectively. From the standpoint of domestic producers, the relevant measure of surplus is unaffected by whether the consumers are domestic or overseas. The determinants of producer benefits in both cases are (a) the size of the research-induced supply shift, (b) the

resulting decline in price, and (c) the initial output. Meanwhile, consumer benefits are given by the area P_0fgP_1 in the ROW and producer losses are shown by the area P_0hiP_1 .

For this study, only the effects on the home country are considered (i.e. only panel a). Since both consumers and producers gain, the national research benefits are unambiguously positive in the home country. The CS, PS, and TS effects in country A are as follows: $\Delta CS_A = P_0C_{A,0}Z(1 + 0.5Z\eta_A)$; $\Delta PS_A = P_0Q_{A,0}(K - Z)(1 + 0.5Z\varepsilon_A)$; $\Delta TS_A = \Delta CS_A + \Delta PS_A$, where: P_0 = pre-research equilibrium world price; $C_{A,0}$ = pre-research consumption in country A; $Q_{A,0}$ = pre-research production in country A; η_A = absolute value of the domestic demand elasticity; ε_A = domestic supply elasticity; Z = relative reduction in price, and K = technical change; vertical shift of the supply function expressed as a proportion of the initial price. Z is calculated using the following formula: $Z = \varepsilon_A K / [\varepsilon_A + s_A \eta_A + (1 - s_A) \eta_{row}]$, where s_A is the fraction of production consumed domestically and η_{row}^E is the absolute value of the elasticity of export demand (i.e. the ROW excess demand).

Figure 2. Large Open Economy Economic Surplus Model



Calculation of net benefits considering research costs and discounting

To evaluate the stream of benefits and costs of the rice research program, the net present value (NPV) and internal rate of return (IRR) were calculated for the marker-assisted rice breeding programs and compared to NPV and IRR for conventional breeding. A 5% discount rate was used for the NPV. Research and development costs were subtracted from the economic surplus benefits year by year beginning with research costs that began on the GCP project in 2005. Research costs included primarily GCP costs for salt tolerant rice in Bangladesh and India and for P-deficiency tolerant rice in Indonesia, but included primarily NARES costs for salt-tolerant rice in the Philippines and Bangladesh. The difference reflects the situation where a mega-variety is modified and directly released following testing in the country as opposed to one where the NARES have to do the marker assisted backcrossing.

Results

The benefits of breeding work to develop salinity-tolerant and P-deficiency-tolerant rice varieties can be presented in two primary ways. First, the varieties developed through marker-assisted breeding can be compared to current varieties in the target countries, and second, they can be compared to varieties developed in an alternative conventional breeding (CB) program. The first set of results indicates the value of breeding to solve salinity and P-deficiency problems. The second set indicates the incremental gains from MAB as compared to CB to solve the two problems. As indicated above, there are also different timelines and research and development costs for different countries and constraints because the GCP project will introduce (a) final varieties for testing in

Bangladesh and India for salt tolerance and in Indonesia for P-deficiency tolerance, and (b) markers and lines that need requires further backcrossing by the NARES in Indonesia and the Philippines for salt tolerance.

The benefits of developing and introducing salinity-tolerant and P-deficiency-tolerant varieties through MAB as compared to utilizing existing varieties are presented in Table 7. These results portray the most likely scenario, but a large number of sensitivity analyses were also conducted that allow the number of years before varietal release, adoption rates, elasticities, discount rate, yield change, and fallow lands brought into production to vary.

Table 7. Economic benefits of marker-assisted breeding for salinity and P-deficiency tolerance as compared to current varieties

| Country and constraint | Year of variety release | Net present value¹ (\$000) | Internal rate of return (%) |
|-------------------------------|--------------------------------|--|------------------------------------|
| Salinity | | | |
| Philippines | 2017 | 220,872 | 111 |
| Bangladesh | 2014 | 3,510,583 | 108 |
| India | 2015 | 4,483,417 | 100 |
| Indonesia | 2017 | 803,494 | 144 |
| P-deficiency | | | |
| Indonesia | 2014 | 1,907,207 | 86 |

1. NPV at 5% discount rate

The estimated cumulative net benefits of saline-tolerant rice from the initiation of the research until 15 years after varietal release (discounted at 5%) are \$221 million in the

Philippines, \$3.511 billion in Bangladesh, \$4.483 billion in India, and \$803 million in Indonesia. These returns represent a very high return on investment of 100 to 144% depending on the country (Table 7). The estimated cumulative benefits for P-deficiency tolerant rice are \$1.907 billion in Indonesia.

The estimated cumulative net benefits of saline-tolerant rice from the initiation of the research until 15 years after varietal release (discounted at 5%) if conventional breeding were used in place of marker-assisted breeding are presented in Table 8.

Table 8. Economic benefits of conventional breeding for salinity and P-deficiency tolerance and incremental benefits of marker-assisted over conventional breeding

| Country and constraint | Year of variety release (Conventional breeding) | Net present value¹ (\$000) (Conventional breeding) | Incremental benefits of MAB over CB (\$000) |
|-------------------------------|--|--|--|
| Salinity | | | |
| Philippines | 2022 | 172,995 | 47,878 |
| Bangladesh | 2017 | 3,032,931 | 477,652 |
| India | 2017 | 4,190,925 | 292,492 |
| Indonesia | 2022 | 629,494 | 174,000 |
| P-deficiency | | | |
| Indonesia | 2017 | 1,647,776 | 259,431 |

The estimated benefits are \$173 million in the Philippines, \$3.033 billion in Bangladesh, \$4.190 billion in India, and \$629 million in Indonesia. The estimated cumulative benefits for P-deficiency tolerant rice are \$1.648 billion in Indonesia. By subtracting the benefits from CB from those for MAB, the incremental benefits of MAB were estimated at \$48

million for the Philippines, \$478 million for Bangladesh, \$292 million for India, and \$174 million for Indonesia for salt-tolerant rice. The incremental benefits using MAB for P-deficiency rice are estimated at \$259 million (Table 8).

Several sensitivity analyses were completed. Increases in yield and adoption percentages increase benefits significantly as expected while increases in supply elasticities lower them. If an additional 5% of the salt affected area is brought into production, benefits increase by 1 to 2 percent. Key sensitivity analyses relate to differences in the time required to release varieties either through MAB or CB. Benefits are reduced by more than a quarter if varieties are delayed by as much as 5 years. Incremental benefits vary dramatically if the differential time lags either increase or decrease. At the one extreme if MAB and CB both take the same number of years, the increment goes to roughly zero. At the other extreme if CB takes five years longer but MAB does not, the incremental benefits almost triple. An example of how the incremental benefits would change is presented in Table 9.

Table 9. Incremental economic benefits for marker-assisted breeding (MAB) compared to conventional breeding (CB) for salt tolerant rice in Bangladesh and P-deficiency tolerant rice in Indonesia as time to release varies with CB (\$000)

| Years | Saline tolerant rice in Bangladesh | P-deficient rice in Indonesia |
|-------------------------------------|---|--------------------------------------|
| MAB 10 years and CB 12 years | 325,976 | 176,955 |
| MAB 10 years and CB 13 years | 477,652 | 259,431 |
| MAB 10 years and CB 14 years | 622,105 | 337,980 |
| MAB 10 years and CB 15 years | 759,679 | 412,789 |
| MAB 10 years and CB 16 years | 890,703 | 484,035 |

Conclusion

Conventional rice breeding typically requires 10-15 years from initiation to varietal release. Marker-assisted breeding is estimated to save at least 2 to 3 years resulting in significant incremental benefits in the range of \$300 to \$800 million depending on the country, abiotic stress, and lag for CB. Salinity and phosphorous deficient soils cause significant losses, and can be difficult problems to solve through conventional breeding because of “genetic load” or undesirable traits that accompany desirable ones during backcrossing. MAB, enabled by advances in genomics and molecular mapping is potentially more precise, time-saving, and cost-effective. It is also clear from our results that solving the salinity and P-deficiency problems is crucial, regardless of whether MAB or CB is used. The net cumulative economic gains using either technique are worth at least \$220 million and as much as \$4 billion over the next 25 years depending on the problem and country.

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