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Charting the CGIAR's Future – Change Design and Management

The Green Revolution at the End of the Twentieth Century

The attached paper was prepared by Prof. Robert Evenson and Dr. Douglas Gollin. It provides a synthesis of the results of the SPIA study on the impact of CGIAR germplasm improvement research. The Chair of SPIA, Dr. Hans Gregersen, will present the results from this study and outline other work in progress.

Category: This item is for Information… Discussion….**x** Decision…

Proposed Action: Indication of the Group's response to SPIA's activities and plans with respect to the impact of CGIAR germplasm improvement research.

CONSULTATIVE GROUP ON INTERNATIONAL AGRICULTURAL RESEARCH

TECHNICAL ADVISORY COMMITTEE

The Green Revolution at the End of the Twentieth Century

TAC SECRETARIAT

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS

April 2001

SPIA Foreword

This paper, written by the leader of SPIA's study of the Impacts of CGIAR Germplasm Improvement Research and his co-author, provides a synthesis of some of the major results of the SPIA study, which will be published as a book by CAB International towards the end of this year (ref. Evenson, R.E. and D. Gollin, eds. 2001. Crop Variety Improvement and Its Effect on Productivity: The Impact of International Agricultural Research. Wallingford, UK: CAB International, 2001).

It draws to a large extent on the work of individual analysts within the CGIAR crop centres that conducted 13 detailed studies and developed data sets on 11 major food crops which are the subject of CGIAR research. The Centres that participated in this SPIA study are CIAT, CIMMYT, CIP, ICARDA, ICRISAT, IITA, IRRI, and WARDA. This work was complemented by country case studies in the three most populated developing countries. Progress reports on this work were presented at ICW 99, MTM 00 and ICW 00.

SPIA is currently developing a proposal on how to follow up on this work by expanding the research to other crops and production sectors, developing a more routine monitoring system on the impact of crop germplasm research, and studying the implications of this study for the methodology of germplam improvement impact research.

Hans Gregersen
Chair
TAC's Standing Panel on Impact Assessment

SDR/TAC:IAR/01/12

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The Green Revolution at the End of the Twentieth Century

Paper prepared for TAC's Standing Panel on Impact Asssessment
by
R.E. Evenson and Douglas Gollin

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The Green Revolution at the End of the Twentieth Century

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Beginning in the 1940s, the international scientific community began an unprecedented experiment: an attempt to use the tools of modern plant breeding to address the pressing food needs of the developing world. Although individual governments had previously sought to improve agriculture in their own domains, there had never been a comparable effort to expand food production globally. The initial movers in this story were two private philanthropies – the Ford and Rockefeller Foundations – and shortly afterwards, the United Nations Food and Agriculture Organization (FAO). The major targets were wheat, rice, and maize production in the developing world.

These early and piecemeal efforts evolved into a large and institutionalized international undertaking in the form of International Agricultural Research Centers (IARCs). A major turning point in this effort was the establishment in 1971 of the Consultative Group on International Agricultural Research (CGIAR), an informal association of public and private sector donors that worked together to support the IARCs. At present, the CGIAR has almost 60 member organizations, and it supports a network of 16 research centers. The CGIAR's budget for 1998 was US$ 349 million.

The philosophical underpinnings for this experiment are best expressed in the 1964 book, Transforming Traditional Agriculture, by T.W. Schultz (Yale University Press). Schultz argued that traditional farmers, *i.e.* farmers using traditional technology, had actually reached an efficient equilibrium. Traditional agriculture could not be transformed by efforts to make it more efficient. Traditional biological technology was not suited to modern input transformation either. Traditional crop varieties were not responsive to fertilizer as was the case in countries with modern biological technology. Nor was it likely that mechanical technology would transform traditional agriculture because, with very low wages, machines, even improved machines, were not cost effective under these conditions. Crop genetic improvement (CGI) offered the most viable transforming opportunity.

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* Robert Evenson is Professor of Economics, Yale University (Robert.Evenson@yale.edu). Douglas Gollin is Assistant Professor of Economics, Williams College (Douglas.Gollin@williams.edu). As indicated below, this paper summarizes major findings from a study conducted by researchers from a number of institutions and disciplines. The study was commissioned by the Standing Panel on Impact Assessment of the Technical Advisory Committee of the Consultative Group on International Agricultural Research. We would particularly like to acknowledge the following individuals who are authors of component chapters of the study: F. Afonso de Almeida, A. Aw Hassan, M.C.S. Bantilan, Y.P. Bi, V. Cabanilla, E. Cabrera, S. Ceccarelli, T. Dalton, S. De Silva, U.K. Deb, A.F. Dias Avila, A.G.O. Dixon, H.J. Dubin, W. Erskine, P.C. Gaur, R. Gerpacio, E. Grande, S. Grando, R. G. Guei, P.W. Heisey, M. Hossain, R. Hu, J. Huang, N. Johnson, S. Jin, G.S. Khush, P. Kumar, M.A. Lantican, J.H. Li, V.M. Manyong, J.W. McKinsey Jr., A. McLaren, M. Mekuria, M. Morris, S.N. Nigam, D. Pachico, M. Rosegrant, S. Rozelle, A. Sarker, K. Shideed, R. Tutwiler, T. Walker, C.S. Wortmann. In addition, we acknowledge specific comments on a draft of this article from Dana Dalrymple, Don Duvick, and Guido Gryseels.

Some of the contributions of this effort are well known. In particular, in the mid 1960s, international researchers helped develop the first "modern varieties" (MVs) or "high-yielding varieties" (HYVs) suited to developing country regions of both wheat and rice. These varieties were rapidly adopted by farmers in some regions of Latin America and Asia, who realized significant production increases as a result. This phenomenon was described in the popular press in as a "Green Revolution."[1]

In subsequent years both supporters and critics of CGI generated analyses of the impacts of the Green Revolution. Critics pointed out that many poor farmers lagged behind in adopting modern varieties, with detrimental effects on income distribution and welfare. Critics also noted that the introduction of MVs was associated with increased use of modern inputs – especially chemical fertilizers and irrigation – with potential adverse environmental effects.[2] Another area of concern has been the displacement of traditional varieties and cultivation systems by modern varieties and production techniques with possible consequences for biodiversity. Critics have highlighted regional inequalities, too: the relative lack of success in Sub-Saharan Africa and in marginal production environments.[3]

Proponents of the Green Revolution have instead focused on the production gains that accompanied the new varieties and on the impacts on hunger, poverty, and human well-being. The population explosion that was being realized in all developing countries after World War II was indeed historically unprecedented. The fact that food production per capita in most developing countries rose in the face of this population expansion was also historically unprecedented.[4]

Both literatures, however, have relied almost entirely on limited data – primarily related to the early diffusion of wheat and rice MVs in the late 1960s through the early 1980s. Little attention has been given to crop genetic improvement in other crops, even though breeding programs have been developed for most food crops. Similarly, little attention has been given to National Agricultural Research System (NARS), even though these programs have produced the bulk of MVs. And little attention has been given to plant breeding contributions in more recent years, even though the past two decades have witnessed larger increments in human populations than occurred in the 1960s and 1970s.

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[1] The early diffusion of modern or high-yielding varieties was documented for rice and wheat by Dana Dalrymple (1986a, 1986b); and for maize by David *et al*. 1988. Stakman *et.al*., 1967, offer a discussion of earlier efforts.

[2] This, of course, was hardly surprising. In fact, the Green Revolution is often treated as a case of induced innovation (Hayami and Ruttan,1985) where declining fertilizer prices made fertilizer responsiveness in plants more valuable. Fertilizer use did increase when modern varieties were introduced, although generally not to levels reached in developed countries. Sub-Saharan Africa, even in the 1990s, used very low levels of fertilizer, because it was still dependent on traditional crop varieties.

[3] We argue in this paper that regional inequities and the failure to produce CGI for marginal production environments were at least partly governed by the initial dearth of research relevant for the crops and growing conditions in Sub-Saharan Africa.

[4] The population expansion beginning after World War II had its origins in health improvements and declining death rates. The dynamics of the expansion were well established by the 1960s. The Green Revolution produced health improvements in later decades, but these came after the "demographic transition" process was well under way.

This paper summarizes the findings of a recently completed study of international crop improvement programs targeted on developing countries.[5] This study provides the most comprehensive picture to date of the impacts of international agricultural research on the developing world. The study documents the production and diffusion of modern varieties for 11 major food crops (including wheat and rice) and covering the 1965 to 1998 period. In this paper we report the central findings of the study and offer an interpretation of the Green Revolution that differs in many respects from earlier studies.

We argue that this more comprehensive perspective calls into question many of the conclusions from the earlier studies. In particular, we show that:

1. CGI gains have been realized in all 11 crops studied. More than 8000 MVs have been produced in these crops for the 1965-1998 period. They were produced in more than 400 CGI programs (both IARC and NARS) in more than 100 countries and by more than 5000 agricultural scientists with long-term commitments to CGI programs. Virtually all of the MVs were the end result of a breeding process entailing, for all CGI programs, literally millions of crosses with subsequent selection and testing, requiring ten years or more of sustained work for each MV produced.[6]

2. The production of MVs in these crops has been dominated by public-sector NARS programs. IARCs have also been extraordinarily successful in producing MVs. Private firms have produced MVs only in hybrid maize, sorghum and millets; and these represent less than five percent of all MVs.[7]

3. International centers have supported NARS breeding programs by providing "germplasm" to them and this germplasm has stimulated NARS CGI investments.

4. The production of MVs has differed by crop and by region because of the high degree of location-specificity of crop varieties, differences in production eco-system conditions and differences in the "germplasm stocks" that are vital to CGI programs.

5. These differences in MV production have resulted in differences in MV adoption rates by crop and region. Breeding programs have responded to eco-system conditions and to MV diffusion experience by incorporating traits (host plant resistance to diseases and insect pests) to produce new "generations" of MVs. This has allowed broader diffusion of modern varieties.

6. Despite the efforts of national and international breeding programs, the production and diffusion of modern varieties has remained uneven across crops and regions.

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[5] The study (Evenson and Gollin 2001) was commissioned by the Impact Assesment and Evaluation Group, now the Standing Panel on Impact Assessment, of the Technical Advisory Committee of the CGIAR. Eight of the IARCs with CGI programs participated in the study. Three country studies (China, India and Brazil) were commissioned as part of the study. The senior author was the Principal Investigator for the study.

[6] It should be noted that some of the MVs included in the study were multiple releases of the same variety. In particular, the varieties crossed by IARCs have tended to be released in multiple countries. For this reason, we estimate that there are perhaps 6,000 distinct releases.

[7] While the IARC programs may be considered to be Non-Government Organizations (NGO) programs, none of the NARS programs was an NGO program.

Thus, farmers in Sub-Saharan Africa received few CGI gains until the 1990s, whereas Asian and Latin American farmers were realizing high rates of CGI gains in all periods.

7. While biotechnology methods will be important in the future, almost all the crop improvement relevant to developing countries over the past forty years has been based on conventional breeding and wide crossing methods.[8]

Production of Modern Varieties

The current study reinforces one of the central lessons from earlier studies of the impact of agricultural research – namely, the importance of targeting research on specific crops and regions. Biological technology cannot in general be transferred from one major eco-system to another; it typically requires extensive adaptation and modification.

<u>Location Specificity of Agricultural Research</u>

In one of the earliest studies of the economics of technology, the late Zvi Griliches (1957) analyzed the pattern of adoption of hybrid corn varieties in the United States. Griliches noted that the dates of initial adoption of hybrid corn differed across U.S. states, as did the subsequent rates of diffusion. For example, following the development of the double-cross hybrid methodology, it took roughly 20 years to the first adoption of hybrid corn varieties in Iowa. It was a further 20 years before the first adoption of double-cross hybrids in Alabama. These time lags were not explained by differences in farmer characteristics or rural cultures; instead, they were explained by the location specificity of maize varieties. In simple terms, the hybrid varieties adopted by Iowa farmers were not of value to Alabama farmers. Alabama farmers did not have access to hybrid corn technology until breeding programs were developed in Alabama to produce varieties suited to local conditions.

A similar phenomenon is apparent in the history of international agricultural research. Hybrid corn (maize) programs were inaugurated in Argentina and Brazil in the 1950s, but it has taken several decades to build germplasm stocks and generate useful breeding materials for subtropical and tropical regions. Based on these efforts (and with scientific leadership from CIMMYT), farmers in Asia (Philippines and India) gained access to hybrid corn varieties only in the 1980s. Farmers in Sub-Saharan Africa are only now acquiring access to this technology.[9]

For many crops and production environments, it has taken decades to develop effective programs of crop genetic improvement. The apparently slow pace of progress in some crops and regions is largely due to the difficulty of developing the location specific stocks of germplasm and know-how.

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[8] Fewer than ten of the 8000 MVs in the study were transgenics. Some transgenic crops have been grown in Latin America after 1996 (maize and soybeans). These were private-sector transgenic varieties.

[9] The 20-year time lag in delivering hybrid maize to Alabama farmers was costly to them, because maize prices declined as costs in other states declined. This same economic penalty for delayed delivery of technology in the case of Sub-Saharan African farmers (75 years) has also been costly to them.

<u>"Quick Results"? Rice and Wheat</u>

Fifty years ago, the two crops most favorably situated to benefit from concerted research were rice and wheat. For these crops, scientists had access both to rich stocks of genetic resources and to extensive breeding experience. In the case of wheat, a breeding program sponsored by the Rockefeller Foundation, located in Mexico and led by Norman Borlaug, was established in 1943. This program eventually evolved into the International Center for Wheat and Maize Improvement (CIMMYT) wheat program. The Rockefeller program drew on previous wheat breeding experience in temperate zone spring wheats (and winter wheats) and had access to substantial collections of landraces (farmer selected varieties) and advanced breeding lines which had been acquired before 1940. This program received a major gain in 1953 when semi-dwarf germplasm was introduced into breeding lines.

For rice, many years of breeding experience, particularly in Japan, had improved *japonica* types in the first half of the 20th century, although *indica* rices remained relatively unimproved. The "ponlai" rice varieties developed in Taiwan in the 1930s combined some of the features of both *japonica* and *indica* types. In the 1950s, the Food and Agriculture Organization of the United Nations (FAO) supported a program of *japonica-indica* crossing. This program set the stage for the subsequent work of the International Rice Research Institute (IRRI).

Given this background, it was not surprising that the first major successes of international agricultural research were in wheat and rice. In both crops, high-yielding varieties suited to developing countries were developed in the mid 1960s. For both crops, the new varieties were based on a new "plant type" with semi-dwarf characteristics.[10] For both crops, farmers adopted the new varieties rapidly in selected areas – chiefly those with access to irrigation. Yields for the new varieties were substantially higher than yields for the varieties that they replaced.

<u>Widespread Production of Modern Varieties:</u>

The striking and rapid success of breeding in these crops has tended to obscure the less dramatic accomplishments in other crops, however. Even in the 1960s and 1970s, there were substantial achievements in other crops. Breeding efforts in both international and national institutions resulted in the production of large numbers of modern varieties.[11]

Figure 1 shows annual releases of "modern" varieties for 11 food crops.[12] The figure shows the high rates of variety production in rice and wheat, but it should be remembered that these crops account for the highest shares of cultivated area in

[10] The semi-dwarf plant type had been originally introduced into wheat by Vogel in 1949. Several early semi-dwarf rice varieties were developed before IR8, the first major Green Revolution rice variety produced at IRRI. The University of the Philippines crossed C4-63, an important MV, at approximately the same time as the cross leading to IR8 was made.

[11] For the crops studied in the IAEG-SPIA report, we identified about 8,000 released modern varieties in the crops and regions under consideration (Evenson 2001).

[12] For brevity, this figure groups together a number of crops. Sorghum, millets and barley are together characterized as "other cereals;" beans, groundnuts and lentils are categorized as "protein crops;" and potatoes and cassava are "root crops."

developing countries. What is perhaps more surprising is the breadth of MV production. Across all crops, regions, and time periods, the data suggest a substantial amount of breeding success.

There are, however, some important disparities in the production of modern varieties. For other cereals, grown primarily under semi-arid and dryland conditions, there was relatively little improved germplasm available at the outset of the period. The same was true for the major pulses and for root crops – especially cassava. The production of MVs in these crops has lagged production in other crops. This effect has been particularly pronounced for the Middle East/North Africa and for Sub-Saharan African countries.

Figure 1 thus shows that:

(a) Modern varieties have been produced for all 11 food crops.

(b) Modern varietal production rates differ by crop reflecting the state of breeding experience and genetic resource development. By the late 1990s, varietal production was roughly proportional to planted area of the crop.

(c) Varietal production for all crops doubled from the 1960s to the late 1970s, then doubled again by the 1990s.

(d) Varietal production rates for wheat and rice have been roughly stable for the past 15 years and have been rising for all other crops.

Adoption of Modern Varieties

In most cases, the modern varieties produced by national and international research institutions have actually been used by farmers. When farmers choose to adopt a new variety in place of an older variety, it reflects the farmer's judgment that the new variety offers some net benefit or advantage. Thus, farmer adoption of modern varieties is a good indication that research is generating appreciable benefits.

Figure 2 depicts adoption rates by region and decade. The figure shows that, for most crops, in most regions, modern variety adoption follows the classic pattern of diffusion described by Griliches. There are, however, important differences across crops and regions in the date of first adoption and in the subsequent rates of increase in adoption. The date of first adoption is not always closely associated with the date of first production of MVs.

Particularly striking are the data on modern variety adoption from Sub-Saharan Africa. Although significant numbers of modern varieties were produced in this region in the 1960s and 1970s, there was little adoption by farmers except for wheat. Why was Sub-Saharan Africa different? In large measure, the data suggest that in the 1960s and 1970s, national and international programs sought to "short-cut" the varietal improvement process in Sub-Saharan Africa by introducing improved varieties from Asia and Latin America, rather than engaging in the time consuming work of identifying locally adapted germplasm and using it as the basis for breeding new varieties. The introduced varieties released during this period were not useful beyond some limited domains, and as a result they had relatively little impact. The pattern remained until the

1980s, when more suitable varieties finally became available. These varieties were based on research focused specifically on Africa – much as the eventual adoption of hybrid corn in Alabama depended on the development of inbred parent lines suitable for conditions in Alabama.

Location-specific breeding thus has been crucial for the adoption of modern varieties across regions and countries. For most of the research institutions involved in crop genetic improvement, the research strategy was first to develop a productive "plant type" (for example, a high-yielding semidwarf) and then to breed in subsequent generations for location-relevant qualitative traits – such as host plant resistance to diseases, pests, and abiotic stresses. This second-stage research was extremely important for adoption. The Indian country study concluded that the first generation of rice MVs (the basic semidwarf plant type) would have been planted on only 35 percent or so of rice irrigated/rainfed area. The subsequent generations of trait incorporation increased adoption to more than 80 percent, with large ensuing benefits for both producers and consumers.

The Contributions of International Research

How much of a role did international institutions play in the development of modern varieties? Figure 3 documents the contributions of international agricultural research centers (IARCs) to the modern varieties released over the 1965-98 period. It also shows IARC contributions to the varieties actually grown by farmers in 1998. We report two indexes of IARC content by crop and crop group. The first is the *Direct IARC* contribution. It is the proportion of all released varieties that were based on a breeding cross made in an IARC program. The second is the *Indirect IARC* contribution. It is the proportion of all released varieties based on a NARS program cross that have at least one ancestor based on an IARC cross.

There are two points of note regarding these data. The first is that IARC content is impressively high. For all crops combined, 36 percent of MVs were based on an IARC cross and 22 percent were based on a NARS cross with at least one IARC crossed ancestor. Fifteen percent of these ancestors were parents, seven percent grandparents and other ancestors.[13]

To put these figures in perspective, note that the IARCs account for only small fractions of the scientists working in crop improvement programs in developing countries – roughly 3 percent of the developing world's maize researchers; about 4 percent of the developing world's wheat researchers; and no more than 15 percent of the rice scientists in South and Southeast Asia, excluding China. The fractions of expenditures on crop improvement in developing countries are somewhat higher, since IARCs spend more money per researcher. Even by this measure, however, the IARC shares of research input are not large. For example, in wheat, international centers probably account for little more than 10 percent of the amount spent by developing countries NARS, excluding China (Heisey *et al*. 2001). Thus, the *Direct IARC* contributions reported above suggest

[13] The proportion of IARC crosses is lower in unique MVs because of higher rates of multiple releases. We estimate that IARC crosses account for 20 to 25 percent of unique MVs.

that the IARCs are contributing to modern varieties far out of proportion to those institutions' shares of scientific manpower or spending.

The second point to note is that there were very few contributions – direct or indirect – from research organizations in developed countries. The agricultural research system in the United States, for example, made almost no Direct contributions and very few Indirect contributions to the Green Revolution.[14] At an aggregate level, the same can be said for research programs in Japan, France and other European countries.[15] This is in itself quite remarkable given the perceived strength of agricultural research in these countries.

Figure 3 also reports a comparison of IARC content in MVs actually adopted by farmers in 1998. This comparison shows that for most crops (rice, minor cereals, protein crops and root crops) the IARC-crossed varieties account for a disproportionately large share of area planted. The sum of *Direct* and *Indirect IARC* contributions is higher for adopted varieties than for released varieties, for all crops except for wheat.[16] Somewhat surprisingly, the highest IARC contributions to adoption are in protein crops and root crops. Across regions, IARC contributions are highest in the Middle East-North Africa and Sub-Saharan Africa, where national breeding programs are generally weak.[17]

Germplasm Effects:

The data on *Indirect* contributions can be used to estimate the contributions of IARCs to the development of modern varieties in NARS research programs. Two channels through which IARC research affects national program releases are relevant.

First, IARCs provide useful germplasm for national programs. A statistical analysis indicates that the doubling of resources in NARS crop breeding programs between 1975 and 1995 would have produced 70 percent more varieties, even in the absence of IARC-developed germplasm. In fact, with these genetic resources available to NARS breeders, varietal production more than doubled over this period. This indicates that IARC germplasm made possible an expansion of the pool of released varieties.[18]

Second, the presence of the IARCs has implications for investment in national crop improvement programs. Theory does not tell us whether international research should "crowd out" national research investments or whether the two are complementary. Based on the data available from our study, however, we find that the complementary

[14] The fact that US breeding programs apparently made few Direct or Indirect contributions to the Green Revolution attests to the importance of location and focus. The IARCs were located in the production environments that they served and mandated to work on varieties for those regions. It should be noted, however, that many of the scientists working in both IARCs and NARS actually received graduate training in developed country programs.

[15] This does not deny, of course, that national programs from rich countries have made important contributions on specific crops or regions; France, to give one example, has made substantial contributions to rice breeding in West Africa.

[16] For wheat, the IARC share of released varieties is very high, so it is not surprising that the IARC share of adoption is lower.

[17] It is perhaps reasonable to say that IARC programs effectively initiated CGI programs for these regions and crops.

[18] The statistical analysis is reported in Evenson (2001). The study used a search theoretic model of plant breeding, which performed better in a statistical sense than a more general specification.

effect dominated the competitive effect. NARS investments in fact appear to have been stimulated by the availability of relevant international research.[19]

Productivity Growth Impacts of CGI Programs

In the end, the impact of agricultural research can largely be measured in terms of productivity gains – which economists define in terms of reducing the amounts of inputs needed to produce a given level of output. Productivity gains lead to improvements in human welfare both because they make more food available at lower prices and because they potentially reduce the amounts of land and other inputs required for agriculture.

The study summarized here included estimates for each crop of the productivity advantages of converting crop acreage from traditional varieties to modern varieties. In some cases, estimates of productivity advantages of converting from early generation MVs to later generation MVs were also reported. Because the crop-by-crop approach may obscure effects across crops, the study also included three country studies for India, China and Brazil. For example, one accomplishment of rice breeding has been to develop varieties with shorter duration to maturity. Such varieties might actually yield less than the longer duration varieties that they replace, making it appear that productivity has fallen. But if these varieties enable farmers to double-crop rice and wheat on land where this was previously not possible, the benefits of rice research might show up as increases in wheat production. The three country studies were designed to pick up some such effects. Interestingly, all three approaches to measuring productivity gains reported similar estimates of impact.

Figure 4 depicts annual crop breeding contributions to growth by crop by decade. These contributions were obtained by multiplying MV adoption rates by the productivity estimates and converting these to ten-year growth rates. These calculations were then compared to actual yield growth over the periods. The calculated growth rates were highly correlated with actual yield changes by crop and region. It was estimated that more than half of the real productivity growth in developing country agriculture can be attributed to crop breeding.[20]

We note from Figure 4 that growth from varietal improvement has been realized in all crops, but at very different rates by region. By the 1990s, all crops except for beans were realizing high growth through varietal improvement.

Regional differences in the effectiveness of varietal improvement reflect differences in crop mix and in rates of adoption. Figure 4 thus goes a long way toward explaining one of the puzzles of the agricultural development literature. Observers have noted that Sub-Saharan Africa and the Middle East-North Africa regions have had

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[19] The estimates of complementarities between NARS and IARC research investments is based on Evenson (2001), which used an instrumental variables approach that included variables determining the demand. One of the important determinants of NARS investment was population. Countries with higher rural population densities invested more in CGI programs. The IARC germplasm effect increased NARS breeding investment by 15 percent.

[20] For countries where MV adoption is low, this contribution is greater.

relatively high "investment intensities" in agricultural research and extension.[21] Yet the productivity performance of these two regions has not matched Asia's record. Figure 4 indicates that in the 1960s Asian agriculture was already realizing significant growth from varietal improvement, while Sub-Saharan Africa was realizing none. In the 1970s and 1980s Asian agriculture was realizing roughly one percent per year from crop breeding alone, while Sub-Saharan Africa was realizing only one quarter as much. Even in the 1990s, Sub-Saharan Africa was realizing only about half the growth of other regions.

For all crops in all regions, the gains from breeding were highest in the 1980s and 1990s. Popular perceptions suggest that the Green Revolution was effectively over by this time, but in fact, as Figure 4 shows, plant breeding contributions were highest for the 1980s – even for rice and wheat. This was particularly important because in most developing countries, the 1980s and 1990s saw the largest increments ever recorded in human populations.

Even with this population explosion, however, crop breeding helped to keep food production per capita rising. As a result, the real price of food declined over the 1980s and 1990s, for the world as a whole and for most developing countries.

Why did Sub-Saharan Africa get so little growth from varietal improvement? Were institutions and policies simply inadequate? Are accidents of geography a fundamental barrier? Are there institutional and political failures? Or is this outcome linked to historically determined cropping patterns and the inherited colonial background? We have argued throughout this paper that the cropping mix and inherited state of knowledge (and of germplasm) are actually the dominant factors in differential regional performance. Yes, there are institutional and political failures in all regions and we do not intend to downgrade these features. But Figure 4 and the data underlying it point to differential research investments and research time lags as the primary reasons for differential performance by region. The implications for Sub-Saharan Africa are actually promising: recent varietal improvement efforts appear to be working, and technological momentum is high for the region.

Counterfactual Scenarios of Economic Effects

The study summarized here also undertook an analysis of the economic consequences of plant breeding research. This analysis compared the actual experience of developing countries with two "counterfactual scenarios" reflecting different levels of agricultural research activity. The analysis was conducted using an international multi-market model developed by the International Food Policy Research Institute (the IFPRI-IMPACT model) and used for a number of widely used projections of agricultural production and trade. The IFPRI/IMPACT model contains 18 agricultural commodities and 37 countries or country groups. The model solves for an economic equilibrium that allows researchers to see how crop yields, crop area, crop production, crop trade and international prices would change under different scenarios. This model also calculates

[21] The ratios of program spending to production value for both research and extension have been as high or higher than comparable investment intensities for Asian agriculture.

two welfare indexes associated with this equilibrium: the percent of children (0-6) malnourished and average food caloric consumption.[22]

The two counterfactual scenarios considered in our research were the following:

1. How would the food and agricultural situation in 1999 have differed if developing countries had failed to achieve any of the actual productivity gains achieved through breeding from 1965 to 1999, assuming that developed countries realized the same productivity gains that they actually realized? This is termed the No Green Revolution (NGR) case.
2. How would the food and agricultural situation in 1999 have differed had international research not been carried out. This is termed the No IARC CGI (NIARC) case. It differs from the first counterfactual in that it assumes that national programs would have invested in research on their own, with varying rates of success across crops and regions.

Both cases are compared to a base case, which incorporates productivity growth components for crops and countries based on actual experience. These are quite high for developed countries because, over the period analyzed, the agricultural sectors in many rich countries – including the U.S. – had higher rates of productivity growth than other sectors of the economy. For developing countries, productivity rates in the base case were also quite high – even without international contributions, NARS research would have increased productivity substantially.

For each counterfactual, "high" and "low" scenarios are reported. The "low" scenario for the NGR counterfactual simply subtracts the modern variety contributions to productivity growth (shown in Figure 4) from base case productivity gains. This essentially corresponds to a world with no productivity growth from plant breeding in developing countries. The "high" scenario assumes that impacts would have been higher because some other productivity gains would have been lost along with the gains from agricultural research. In particular, it was assumed that one-fourth of the non-CGI gains would have been lost as well.

The NIARC simulation was constructed by subtracting all the benefits associated with international research. The "low-impact" and "high-impact" scenarios were based on different assumptions about the response of national programs to the loss of IARC research. The "low" scenario presumed that NARS programs would have compensated for the loss of international research by producing 50 percent more MVs than they actually did. The "high" scenario presumed that they would have produced only 25 percent more MVs than they actually did. This simulation also assumed that productivity in developed country agriculture would have fallen by an amount consistent with estimates of the impacts of the IARCs on agricultural productivity in those regions (from Pardey *et al*.).

Figure 5 shows how food prices in developing countries would have responded to the two counterfactuals (four scenarios). Other impacts are shown in Figures 6 and 7 and depict a range of effects.

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[22] The IFPRI-IMPACT model has been widely used in IFPRI's 2020 projections. However, it can also be used for backcasting counterfactual simulations.

Consider the NGR (No Green Revolution) case. This comparison suggests that in the absence of genetic improvement in developing countries, prices of food crops would have been 35 to 66 percent higher in 1999 than they actually were. Many observers are surprised that these price effects are not larger. The main reason is that for a number of crops – including wheat and maize – the ensuing production reductions in developing countries would have been offset by increased production from rich countries, which would have responded to higher prices by expanding production. Moreover, in some crops – such as other grains, potatoes and root crops – the price increases that would have occurred are modest because there were relatively low gains in productivity from genetic improvement. For these crops, the absence of research would have made little difference on prices.

The effects of the NGR counterfactual are further illustrated in Figure 6, which shows that developed country yields, areas and production would all have risen if developing countries had failed to generate productivity gains through research. In the developing countries, the slower productivity growth would have implied reduced yields and production (compared to what actually happened). The area under cultivation would have expanded, however, due to price effects. Because food prices would have been higher, more area would have been devoted to food production in both rich and poor regions. This in turn would have had substantial implications for the environment. Cropland increases must come at the expense of other land uses. This has implications for soil and water erosion and biodiversity. The Green Revolution, interpreted in this light, spared land for nature. And the quantity spared is significant.[23]

Yield losses in developing countries – and the implied production losses – would not have been translated directly into consumption losses. In the absence of the Green Revolution, developed countries would have exported more to developing countries, making up for some of the production shortfalls. The extent of this trade would have been limited, however, by the capacity of importers to pay for food imports.

The NIARC counterfactual generally runs parallel to the NGR counterfactual described above. Under this scenario, continued research by national programs in developing countries would have led to a Green Revolution, but of reduced magnitude. As a rough generalization, this "lite" Green Revolution would have been about 60 percent of the magnitude of the one actually achieved.

Figure 7 shows welfare consequences of the counterfactuals and scenarios. Had the Green Revolution not occurred, the percent of children (0-6) in developing countries deemed to be malnourished (based on weight and height) would have been six to eight percentage points higher than it was. For South Asia, it would have been 12 to 15 percentage points higher. Put in perspective, this suggests that the Green Revolution succeeded in raising the health status of 32 to 42 million pre-school children. The effects on calorie availability are also large and these also have very important implications for welfare.[24]

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[23] Note that land is spared for nature in all countries because agricultural prices are lower.

[24] Calorie availability affects all segments of the population, not just the poor. Access to more food at lower prices is important for both urban and rural populations.

Retrospective

The Green Revolution was clearly important to the welfare of millions of relatively poor people in developing countries. To the extent that traditional agriculture has been transformed in developing economies, it was the crop improvement programs associated with the Green Revolution that were the driving force for transformation. More important, technology pipelines have been established in many countries, providing technological momentum for the future. Institutional changes necessary to development have been facilitated.

Some of the criticisms of the Green Revolution perhaps reflect unreasonable expectations or standards. For example, it is unrealistic to imagine that breeding programs in developing countries could have produced varieties that needed less fertilizer or water than the leading varieties available in developed countries. Nor is it reasonable to fault plant breeding programs for failing to achieve development goals such as improving the distribution of income. Such goals might be desirable, but they are perhaps unrealistic. These criticisms also fail to compare the Green Revolution against an appropriate counterfactual. In spite of the Green Revolution, life remained desperately difficult for billions of people in poor countries. But the question we must ask is: what would have happened in the absence of the Green Revolution? Would the developing world have arrived instead in a pre-industrial utopia in which populations grew but remained self-sufficient and food secure, and in which few inputs were used while income distribution improved? Our calculations suggest not.

Would the Green Revolution have occurred even without investments in international research? Clearly some productivity gains would have been achieved. National research programs in would have filled some of the void. But this would not have happened automatically. The data suggest that agricultural research programs in developed countries, including the US experiment station system, did not create and would not have created the Green Revolution, in the absence of international research. National programs in developing countries would have done more – particularly had they enjoyed increased support from development agencies and national governments. Our counterfactual calculations suggest that something like 50 to 60 percent of the Green Revolution might have been achieved without the IARCs.

As it happened, however, the international research system made major contributions across crops and regions, including both Direct contributions (*i.e.* through crossing, selection and varietal releases) and Indirect contributions (through contributions to the efforts of national programs). Many of the Direct contributions effectively laid the groundwork for breeding in crops and regions that had previously been neglected (e.g., beans, cassava, maize in Africa). Indirect contributions made many small and isolated NARS programs more productive.

Certainly there were management and design failures in many of the NARS programs and the IARC programs. And assessed against broad development objectives, the Green Revolution fell short in many ways and deserves criticism. Assessed against more realistic and practical counterfactual conditions, the Green Revolution transformed traditional agriculture in many countries and initiated broader processes of development.

Most important, it improved access to food and nutrition for hundreds of millions of the poorest people on earth.

But the task of responding to population-driven increases in food demand is only partly completed. Population momentum effects guarantee continued increases in population in coming decades. There is technological momentum, too: past research creates the prospect of continued improvements in crop varieties.

A number of projections of supply and demand over the next two decades show that this technological momentum is likely to enable food consumption per capita in developing countries to continue to rise.

But achieving global food supply objectives is in fact not the central argument for continued and expanded investment in crop improvement programs. If developing countries mired in mass poverty are to make progress in reducing that poverty, they must achieve more production from the resources that are available to them. They must achieve transformations of production systems that set in motion the dynamics of investment and productivity gains that are necessary. Crop improvement programs, for most of the poorest countries of the world, have the potential to transform agriculture and to initiate the broader development that is required.

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Figure 1. Modern Variety Production by Decade and Region (Annual MV Releases)

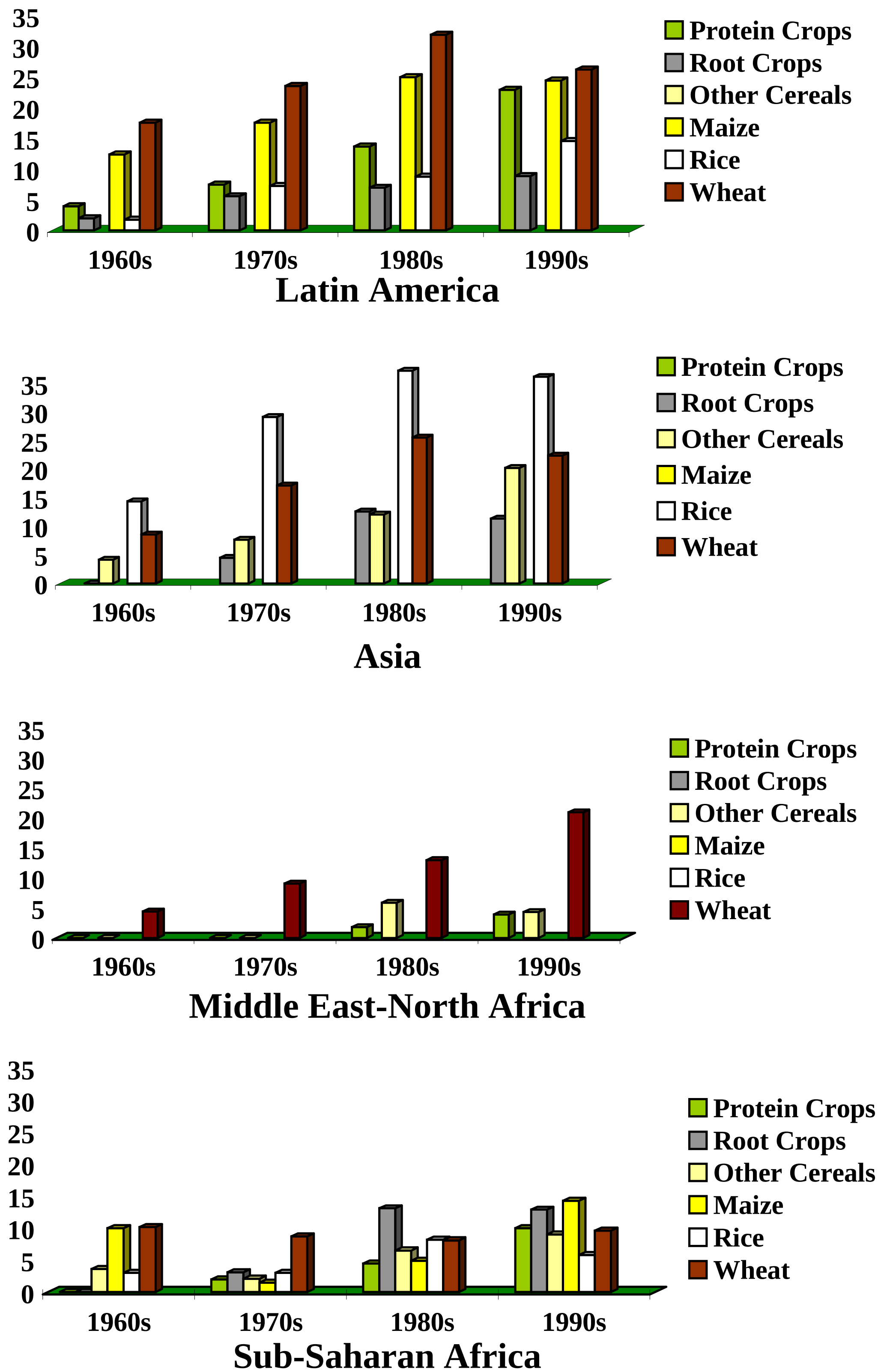
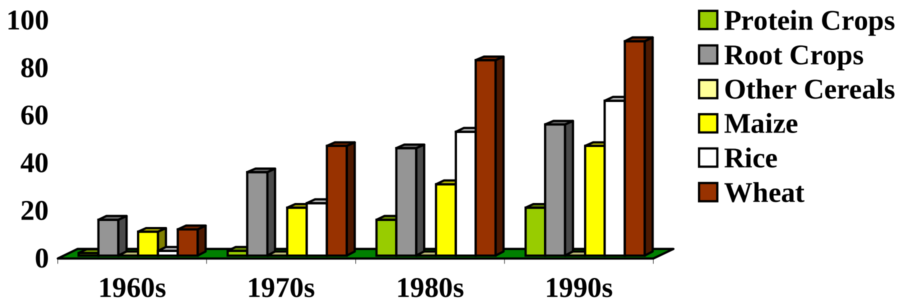
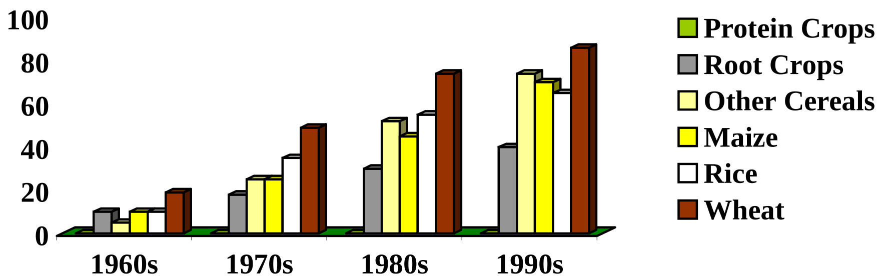


Figure 2. Modern Variety Diffusion by Decade and Region

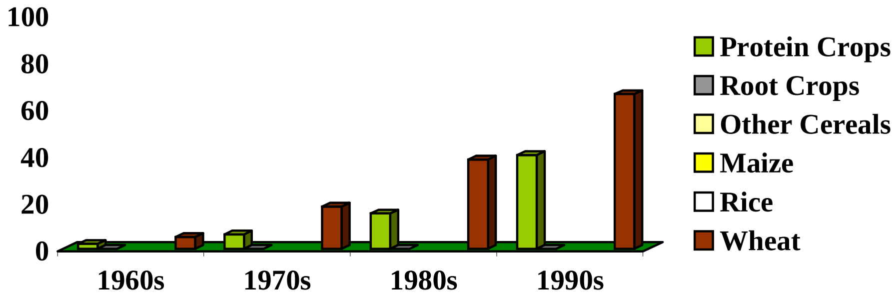
Percent Area Planted to Modern Varieties



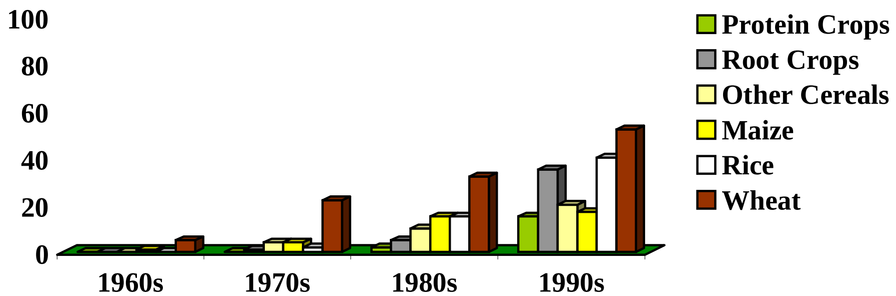
Latin America



Asia



Middle East-North Africa



Sub-Saharan Africa

Figure 3. IARC Content in MVs

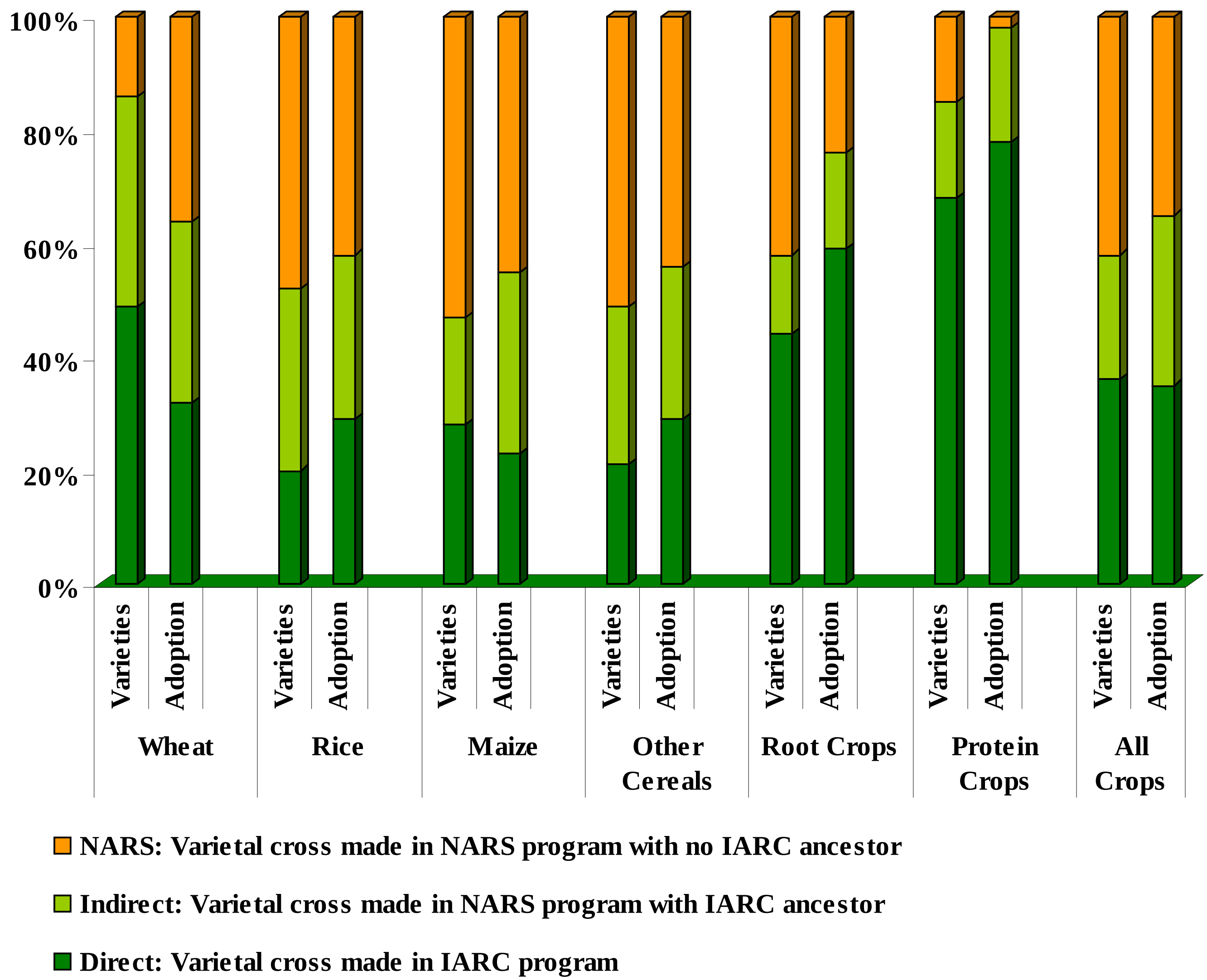


Figure 4. Annual Growth Contributions of Modern Varieties

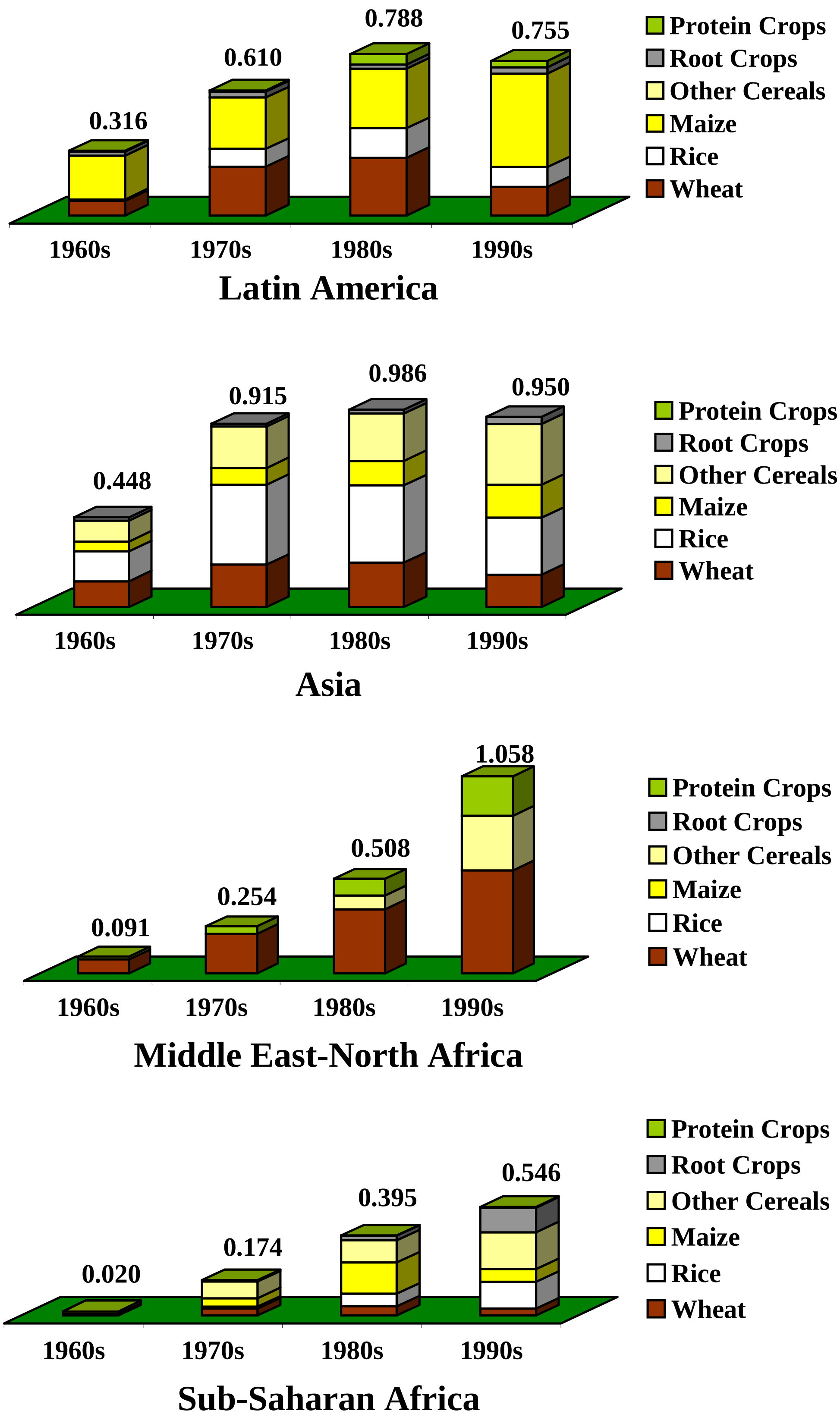
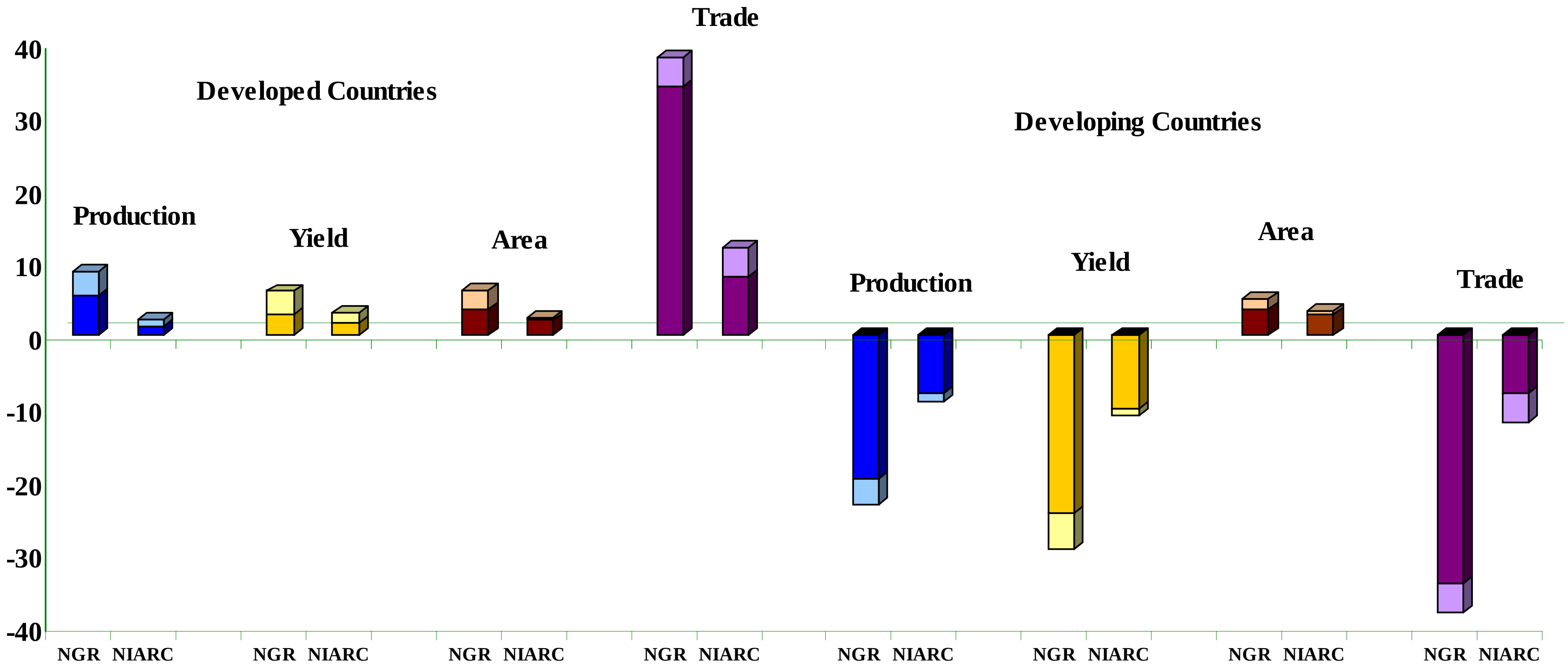
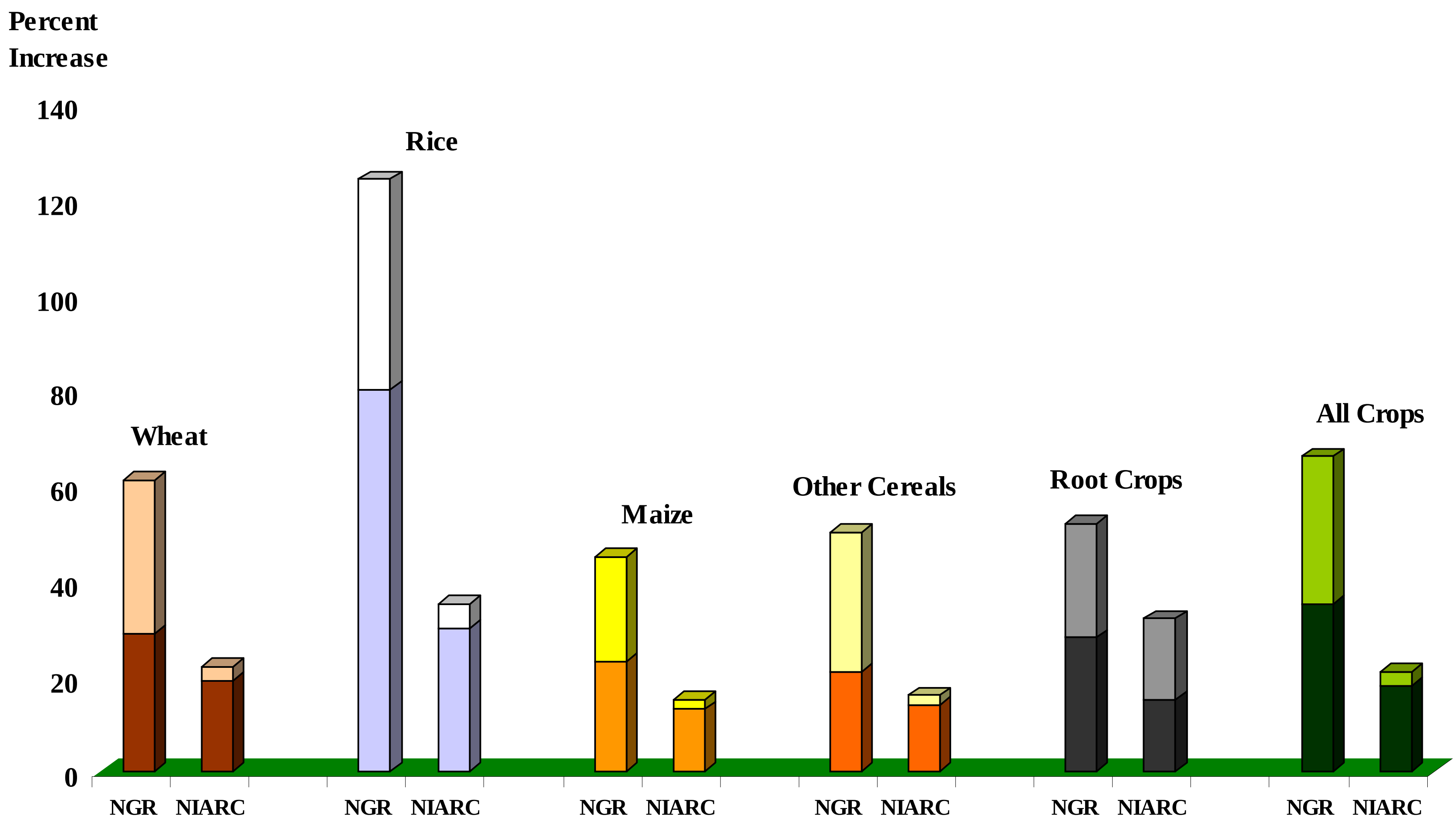


Figure 5. Production, Area, Yield and Trade Effects: All Crops: Counterfactual Simulations.



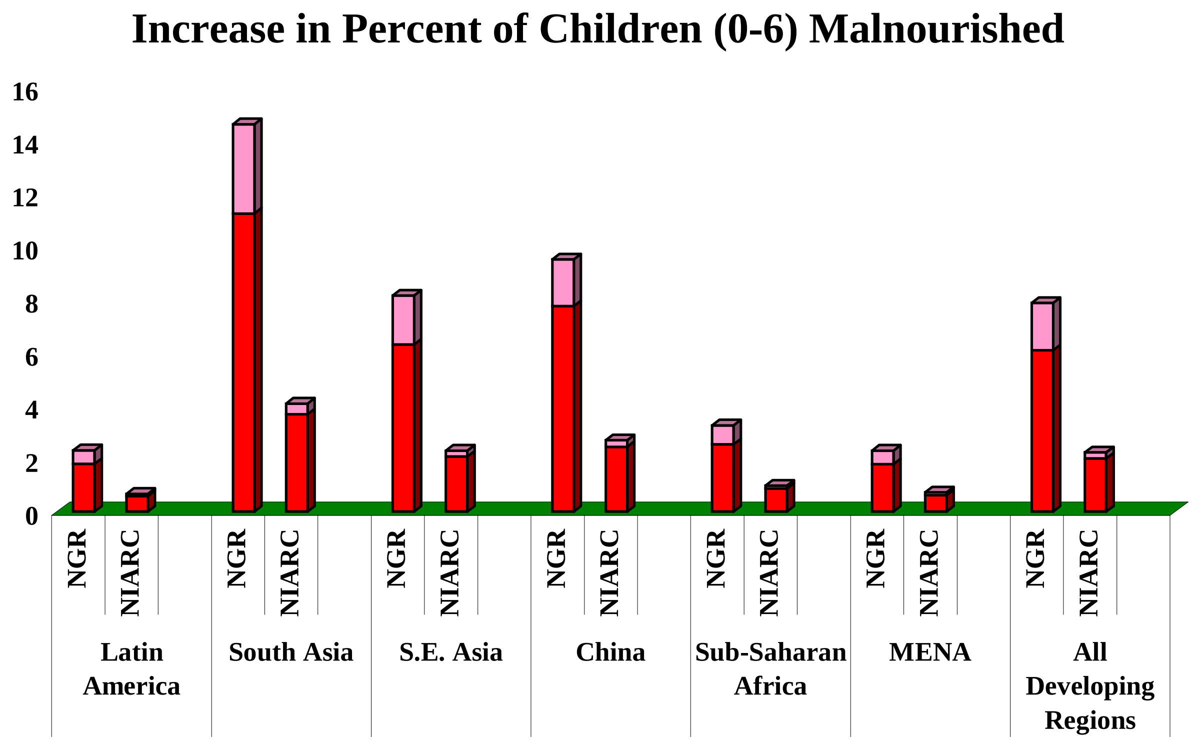
NGR: Simulations in percent differences if production in developing countries is constrained to use varieties available in 1965.
NIARC: Simulations in percent differences if IARC CGI programs bad not been built.

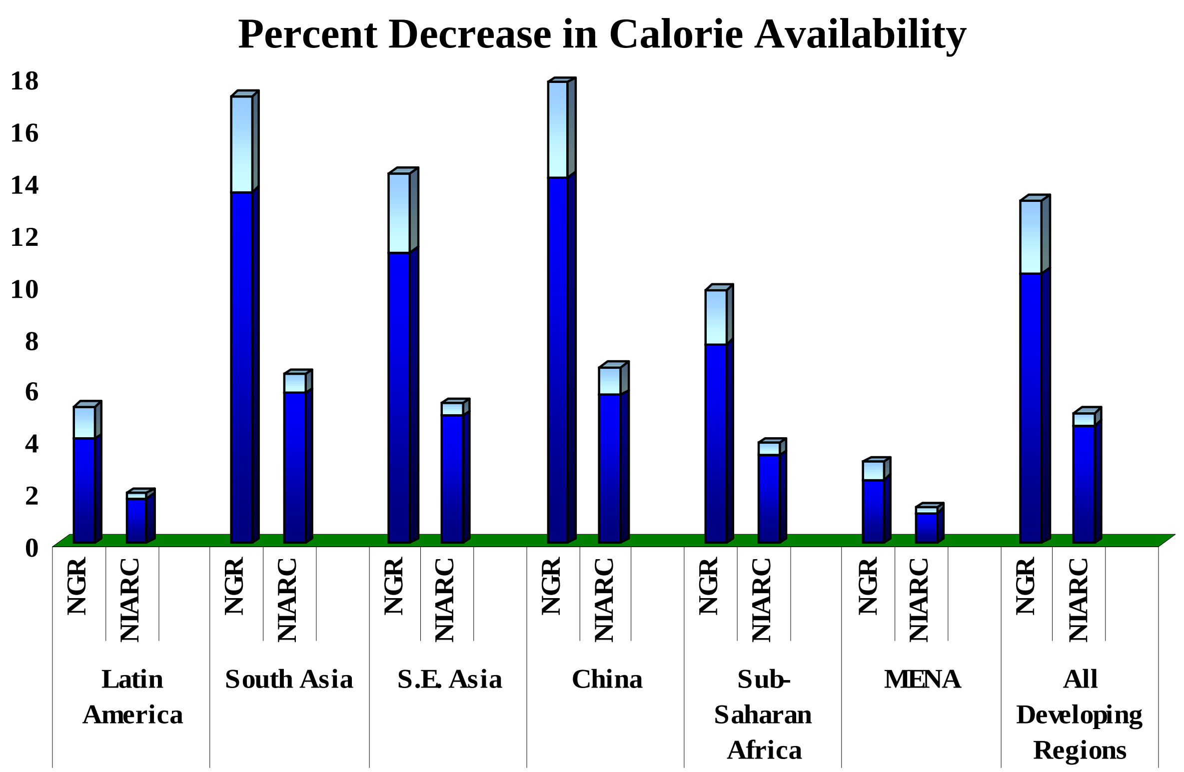
Figure 6. Global Price Effects: Counterfactual Simulations



NGR: Simulations in percent differences if production in developing countries is constrained to use varieties available in 1965.
NIARC: Simulations in percent differences if IARC CGI programs had not been built.

Figure 7. Welfare Indexes: Counterfactual Scenarios





NGR: Simulations in percent differences if production in developing countries is constrained to use varieties available in 1965.
NIARC: Simulations in percent differences if IARC CGI programs had not been built.