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Productivity Gains from Rice Genetic Enhancements in West Africa: Countries and Ecologies

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Summary. — Many critics claim that public research in West Africa has failed to develop technological innovations to improve productivity and stimulate economic development in the agricultural sector. Using Griliches' method of estimating the impact of a research induced supply shift, this study finds that rice varietal improvement generated a producer surplus gain of approximately US$360 million in 1998 in the seven most important rice-producing countries of West Africa. Eighty-one percent of this gain has occurred in the irrigated and rainfed lowland ecologies which occupy just 12% and 35% of total regional rice area respectively. By contrast, approximately US$5.6 million is invested annually in regional varietal improvement research.

Key words — West Africa, rice, agricultural research, impact

1. INTRODUCTION

Many critics claim that public research in West Africa has failed to develop technological innovations to improve productivity and stimulate economic development in the agricultural sector. This study estimates to what extent rice genetic enhancement, long the cornerstone of an integrated strategy to improve productivity, has increased rice output and generated regional economic gains. In addition, this estimate is disaggregated by country and rice ecology in order to highlight the disparate distribution of the impact. In order to improve research priority setting recommendations, the study indicates the role of traditional African germplasm, imported genetic material from Asia and national, regional and international institutions in rice productivity growth.

The volume of rice consumed in West Africa exceeds US$2.75 billion annually and is largely composed of US$1.85 billion in production and US$0.9 to US$1.0 billion in imports when valued at a regional import parity price of US$225/mt. Overall, West Africa imports approximately 12% of the 24.8 million metric tons of rice traded each year. This study focuses on seven of the most important producers of rice within the region: Nigeria, Guinea, Côte d'Ivoire, Sierra Leone, Mali, Ghana and Senegal. Combined, these countries produce approximately 91% of the region's rice and represent about 91% of all area under rice cultivation.

Rice is a versatile and adaptive crop that can be produced from the cold-water mountain highlands to the brackish coastal mangrove swamps. Across the region, rice is grown in five distinct ecologies. The most intensively cultivated systems are found in the irrigated

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perimeters of the Sahelian zone of Senegal, Mali and Nigeria and the least intensive in upland (dryland) areas of the humid tropics. The uplands cover a vast area ranging from the Casamance in Senegal to southeastern Nigeria. By contrast, recent areal expansion has been concentrated in the rainfed lowlands without complete water control throughout the region. This ecology now challenges the traditional uplands as the largest growing environment (Table 1). The mangrove swamps, found along the southwestern shores of Sierra Leone, Guinea and Senegal and the deep-water floating ecologies, cultivated along West Africa's major rivers—the Niger in Mali, the Benoué in Nigeria—remain minor production ecologies.

Research on rice improvement in West Africa originated more than 65 years ago in national agricultural research programs and collaboration with international agricultural research centers began in the 1960s. Currently, regional rice research is conducted by national and international agricultural research centers with support from global germplasm networks and several bilateral development organizations.

While many studies attempt to derive the economic surplus effects of complementary seed and crop management technology packages, this study will focus on the benefits derived from plant breeding and varietal purification only as this has been the primary source of technological change. Genetic enhancement of rice has a long history in West Africa beginning with the domestication of *Oryza glaberrima* (African rice) in the Central Niger Delta basin around 3,500 years ago (Carpenter, 1978). *O. glaberrima* was carried westward into the humid tropics of modern Senegal, Guinea, Guinea Bissau and Sierra Leone. Since that time, farmers have selected African rice plants with desirable traits, such as disease resistance, yield, palatability or storability. *Oryza sativa*, (Asian rice) however, was first transported to West Africa by Portugese explorers over 500 years ago on their return from India (Carpenter, 1978). "Traditional" varieties, well adapted to local growing conditions, have evolved from subsequent introductions of *O. sativa* and centuries of farmer selection.

Rice does not need pollen from another plant to reproduce and exchange of genes largely occurs only through deliberate crossing. Asian and African rice species coevolved in the region but rarely, if ever, have exchanged genetic materials due to incompatibility between species. Previous scientific attention and genetic enhancement largely concentrated on improving Asian rice species until the early 1990s when these two species were crossed successfully by rice breeders. The resulting interspecific crosses could lead to substantial productivity gains in the upland ecology where improved cultivars have been less effective than in the lowlands. Since these interspecific crosses were not widely disseminated prior to 1998, this study focuses on quantifying the extent to which science has improved the productivity of Asian rice species for West Africa.

In order to do so, Section 2 will present a discussion of regional resources invested annually in genetic enhancement and the institutions involved therein. Section 3 describes the production and release of improved varieties by rice ecology, the lineage of genetic property, and derives field-level diffusion estimates. Section 4 evaluates the economic impact of genetic enhancement by estimating national- and eco-

Table 1. *Study countries and West Africa regional production and area summary (1998)*

	Rice area ('000 ha)	Production ('000 mt)	Yield (mt/ha)	% Area in ecology				
				Rainfed upland	Rainfed lowland	Irrigated lowland	Mangrove swamp	Deep-water floating
Nigeria	2,044	3,275	1.60	35	45	12	0	8
Guinea	503	764	1.52	69	19	1	11	0
Côte d'Ivoire	482	1,197	2.48	74	19	7	0	0
Sierra Leone	285	328	1.15	67	22	2	7	2
Mali	330	705	2.13	3	25	32	0	40
Ghana	130	194	1.48	9	81	10	0	0
Senegal	45	124	2.72	5	43	45	7	0
Study total	3,819	6,586	1.87	45.6	34.2	11.1	2.0	7.2
Regional total	4,206	7,273	1.73	43.3	35.2	12.1	2.8	6.9

Source: FAOSTAT (2002); survey results.

system-specific producer surplus gains, by source of genetic improvement, in 1998. The economic implications of this analysis are summarized in the final section.

2. NATIONAL AND REGIONAL RESOURCES FOR GENETIC IMPROVEMENT

Over the past 30 years, numerous international organizations have contributed to regional rice development in West Africa. These include three international agricultural research institutes and many bilateral development programs. Several national agricultural research institutes (NARS) have long histories of varietal improvement facilitated by bilateral assistance: Côte d'Ivoire, Mali and Senegal and Guinea. The primary collaborative partner for the first three countries was French led, originally through IRAT, *Institut de Recherche Agronomique Tropicale*, and later through CIRAD, *Centre de Coopération Internationale en Recherche Agronomique pour la Développement*. In 1963, IRAT recorded its first crosses in Senegal where a collaborative program existed in the Casamance until 1973. Through this effort, eight crosses where registered for the rainfed lowland and upland ecologies of the Casamance region (CIRAD-CA, 1993). By contrast, the program in Côte d'Ivoire lasted for over 20 years and 44 separate varieties were catalogued, many of which were released recently by the Ivorian government. In Mali, collaboration lasted for a short period in the early 1970s and for an eight-year period in the 1980s and 1990s. Four varieties were catalogued and one released in 1980 for the deepwater floating ecology.

In Guinea, large-scale bilateral assistance has been, and continues to be, received from the North Korean government. The North Korean government developed the Kilissi agricultural research station in the early 1980s to serve the region. Considerable improvement has occurred in breeding varieties tolerant to problem soils for the rainfed lowlands and many of these varieties are used in crossing programs throughout the region.

In conjunction with bilateral assistance programs, three international agricultural research institutes have contributed to regional varietal improvement over the past 35 years: the West Africa Rice Development Association (WARDA), the International Institute for Tropical Agriculture (IITA) and the International Rice Research Institute (IRRI). WARDA was formed as a regional association in 1971 by 11 countries with assistance from the United Nations and the Economic Council for Africa. It later expanded membership to 17 countries. WARDA's original mandate was very broad including research, training, development and policy formulation. Germplasm improvement research emphasized region-wide adaptive field trials using direct introductions of exotic materials from outside the region. During the same period, IITA conducted research on genetic improvement at its Nigeria headquarters and served as liaison to genetic materials located outside of the region. The primary mechanism used to transfer Asian and Latin American breeding lines to Africa, and to transfer African lines within the continent, was known as the International Rice Testing Program (IRTP, subsequently renamed the International Network for the Genetic Evaluation of Rice, INGER). During 1975–98, 243 improved rice varieties and 28 landraces from African countries were tested through the INGER network and subsequently released by national authorities (Chaudhary *et al*., 1998).

In many countries, the history of varietal improvement began before the advent of the Consultative Group on Agricultural Research (CGIAR). In the 1960s and 1970s, these programs were the first to incorporate early Asian advances in germplasm improvement into their varietal development programs. The most notable example of a long-term varietal improvement program is in Nigeria where the National Cereals Research Institute (NCRI) has conducted varietal improvement research for nearly 50 years.

The national program in Nigeria has the greatest number of post-graduate trained rice research scientists within the region. The first official rice varietal release occurred in 1954 with BG79 for the rainfed lowland ecology. Since then, 50 more rice varieties have been released at fairly regular intervals and recent estimates indicate that approximately 90% of all rice area is planted to improved varieties. The most sizable yield advances have occurred in the rainfed lowland and irrigated ecologies.

In comparison with the national focus of the Nigerian program, the Rokupr Rice Research Station in Sierra Leone, where British and Sierra Leonean scientists have been working since the 1934, has served as the locus for regional mangrove rice improvement (Matlon, Randolph, & Guei, 1998). Early efforts focused on varietal adaptation to saline and sulphate acid conditions found in the mangrove swamps and, in the 1960s, advanced into breeding new seed lines. Rokupr also concentrates on varietal development for the lowland ecology. In many mangrove areas, modern varieties have been introduced only in the last ten years but uptake has been rapid. Adesina and Zinnah (1993) estimate that during 1986–90, the percentage of farmers growing modern varieties increased from 17% to 56% in Sierra Leone, and from 0% to 17% in Guinea. Their analysis found modern mangrove rice varieties generated a total of $14 million worth of economic benefits for Sierra Leone during 1986–90 and $0.4 million for Guinea over the same five-year period. Tré (1995) and Seidi (1996) also evaluated the impact of modern varieties but in terms of the return to research investment. Tré (1995) estimates the internal rate of return (IRR) for mangrove rice research in Sierra Leone to be between 18% and 21%, whereas Seidi (1996) reports an IRR of 26% for rice research and development efforts targeted at an important production zone in Guinea Bissau. By contrast, development of ROK 14, an improved variety for the lowlands identified in the late 1970s by Rokupr, was estimated to cover 22% of national rice area and cultivated by 90% of lowland farmers in 1993 (Edwin & Masters, 1998). This study found that investment in the development of ROK 14 generated an annual rate of return of approximately 34% by 1993.

Despite isolated cases of strong and concerted effort on varietal improvement, regional human capacity in rice improvement remains limited (Table 2). Of the 106 scientists actively participating in rice research in the national programs, 19% possess a B.Sc. level degree, 51% a Masters degree and less than 30% a Ph.D. National research programs are supported by WARDA where one-third of scientific effort is allocated to varietal improvement, a figure consistent with that of national programs. Approximately 46 scientists years of research time are allocated to breeding and supporting science for varietal improvement in the region annually. On a regional scale, 79% of all plant improvement activities are allocated to cultivar development work, 9% is allocated to basic research, nearly 9% into strategic pre-breeding work and 3% into genetic resource management.

While most countries have a team of scientists allocated to varietal improvement, limited operating funds and weak capital infrastructure for genetic resource management hinders national efforts in plant breeding and genetic conservation. Although specific breakdown of national program investment in varietal improvement was not available for any country, most provided total annual expenditure on all rice research activities. Nigeria, for example, expended under US$145,000 for their entire rice research program in 1997 (Ojehomon, Wayagiri, Tiamiyu, Maji, & Misari, 1999). Total expenditures at Rokupr Rice Research station are about US$120,000 per year (Sama S. Monde, personal communication). Using the purchasing power parity index (PPP) [1] to control for relative cost level differences between countries, these expenditures equal US$395,658 and US$331,034 for Nigeria and Sierra Leone respectively. By contrast, WARDA allocates slightly more than US$2.2 million annually (US$3.3 million at PPP) [2] (WARDA, 1999). Investment by WARDA includes core budget allocations and targeted bilateral contributions from development agencies, foundations and international organizations. Based upon these figures, direct financial investment for varietal

Table 2. *Human capacity allocated to varietal improvement in West Africa, 1998 (scientist years)*

Country	Breeding	Agronomy	Entomology	Pathology	Weed science	Soils	Other	Total
Nigeria	2.2	1.9	0.4	0.1	0.2	0.2	0.3	5.3
Guinea	6.2	2.4	–	0.8	–	–	–	9.4
Côte d'Ivoire	2	–	–	0.1	–	–	1.0	3.1
Sierra Leone	4	0.3	0.4	0.6	–	0.6	0.4	6.3
Mali	2.8	0.6	0.3	0.3	0.3	–	0.1	4.4
Ghana	1.7	1.6	–	0.6	0.3	1.1	0.2	5.5
Senegal	0.6	0.3	–	0.2	0.2	0.4		1.7
NARS total	19.5	7.1	1.1	2.7	1	2.3	2	35.7
WARDA	2.3	1.0	0.3	0.3	0.3	0.2	5.5	9.9
Regional total	21.8	8.1	1.4	3	1.3	2.5	7.5	45.6

Source: Survey results.

improvement within the region did not exceed US$3.2 million (US$5.6 million at PPP) annually in 1998. Two important regional bilateral investments are not captured in this estimate: that made by North Korea in Guinea and by France through CIRAD in Mali. The ratio of investment in rice varietal improvement to the value of regional production is slightly more than one-quarter of 1%. By contrast, the ratio of research expenditures to agricultural gross domestic product equaled seven-tenths of 1% in 1991 for nineteen African countries (Pardey, Roseboom, & Beintema, 1996).

Concurrently, few national programs pursue large-scale breeding programs and fewer maintain *ex-situ* germplasm collections. Nigeria, for example, requests germplasm annually from advanced research institutes or draws upon *in-situ* released varieties for crossing purposes. In Mali, as in most other countries, parents used in crossing are regenerated biannually which limits the number of feasible crosses. As with Nigeria, this is due to the lack of a cold storage facility for long-term germplasm conservation. When compared with advanced research facilities with germplasm storage capacity, this limits the pool of varieties that can be drawn upon for crossing in breeding programs. The largest block of varieties used by a NARS in a breeding program was found at the Malian irrigated rice research station in Niono where 1,500 varieties are retained. Most countries, however, maintain crossing blocks of between 100 and 250 entries. Region wide, only 87 crosses were made by national programs in 1998, 73 of which occurred in Guinea. Many scientists indicated that they crossed varieties everyother year in order to allow evaluation of early generations before making additional breeding crosses.

3. REGIONAL PRODUCTION AND RELEASE OF IMPROVED VARIETIES

Despite limited regional resources invested annually in varietal improvement, 197 improved varieties have been released (Table 3). Varietal release has been relatively stable through the last 20 years with the exception of the early 1990s. On the average, about eight varieties per year have been released since 1980. A substantial number of new varieties are projected to be released during the period from 2000–04 but these are not included in the impact calculation.

Regional collaboration has produced a considerable number of new varieties for two ecologies: the mangrove swamps and irrigated. These two ecologies have the highest number of releases per hectare of cultivation. The institutions responsible for the development of these varieties, and their genetic origination of the enhancement, have been diverse. As indicated in Section 2, several public and international institutions have worked simultaneously on varietal development. In order to differentiate between sources of genetic material and the institution responsible for enhancement, seven mutually exclusive content categories were developed. Each variety was assigned, based upon its pedigree, to one of the categories. The content categories are:

(1) "Center Cross-Center Selection"—varieties that were crossed by a CGIAR center and whose subsequent selection was conducted by a CGIAR breeder;
(2) "Center Cross-NARS Selection"—varieties that were crossed by a CGIAR center and whose subsequent selection was conducted by a national program scientist;
(3) "NARS Cross-Center Parent"—varieties produced by a national program using at least one CGIAR center parent;
(4) "NARS Cross-Center Ancestor"—varieties produced by a national program using at least one CGIAR grandparent;
(5) "NARS Cross-NARS Ancestor"—varieties produced by a national program using a parents produced by a national program;
(6) "Landrace"—Genotype introduction of a traditional variety; and,
(7) "Unknown Improved Content"—an improved variety of unknown heritage.

The content of the released varieties was discernible with precision. Eighty of the 197 varieties catalogued by the study (40%) were developed by national programs using genetic material that originated within national programs (category 5) without any direct or indirect involvement of the CGIAR. This category also includes the products of bilateral collaboration, for example with CIRAD. Thirty-eight of the 80 varieties in category 5 were produced wholly by IRAT (CIRAD) and 13 by the Rokupr Rice Research station. The Rokupr station also produced several more rice varieties for the mangrove ecology using materials developed by IRRI in conjunction with WARDA. The second most important category, accounting for 54 of the 197 varieties of the releases (27%) was of the other extreme:

Table 3. *Varietal release history by country and ecology*

Country and ecology	Pre-80	80–84	85–89	90–94	95–99	00–04	Total
Nigeria							
Irrigated	–	–	7	–	4	6	17
Rainfed lowland	7	4	3	1	–	7	22
Upland	1	1	6	5	–	9	22
Mangrove	–	–	–	–	–	1	1
Guinea							
Rainfed lowland	–	–	3	–	5	6	14
Upland	–	–	–	2	2	5	9
Mangrove	6	–	1	4	2		13
Côte d'Ivoire							
Irrigated	3	3	1	–	5	2	14
Rainfed lowland	4	3	1	–	1	2	11
Upland	6	7	–	–	14	4	31
Sierra Leone							
Irrigated	3	–	4	–	–	–	7
Rainfed lowland	–	–	6	–	–	–	6
Upland	1	–	7	–	1	–	9
Mangrove	5	–	1	2	–	6	14
Mali							
Irrigated	4	2	3	3	1	11	24
Rainfed lowland	–	2	1	–	–	11	14
Upland	1	–	–	–	–	10	11
Floating	3	2	–	–	–	2	7
Ghana							
Irrigated	–	–	1	–	1	11	13
Rainfed lowland	–	2	4	–	1	11	18
Upland	–	–	–	–	–	10	10
Senegal							
Irrigated	2	–	–	3	2	7	14
Rainfed lowland	2	1	2	–	4	–	9
Upland	–	3	–	–	1	–	4
Mangrove	–	–	1	–	3	1	5
Total							
Irrigated	12	5	16	6	13	37	89
Rainfed lowland	13	12	20	1	11	37	94
Upland	9	11	13	7	18	38	96
Floating	3	2	–	–	–	2	7
Mangrove	11	–	3	6	5	8	33
Grand total	48	30	52	20	47	122	319

Source: Survey results.

varieties developed by the CGIAR with genetic material developed by the CGIAR (category 1). The third most important source of released varieties, purified landraces (category 6), consisted of 27 of 197 or 14% of accessions. This category includes traditional varieties introduced from outside of the region and also those transferred from one African nation to another within the region. By contrast 31 of 197 varieties (16%) were developed collaboratively by national and international agricultural research institutes. In all but three cases, the national programs conducted the varietal crosses using genetic material developed by the CGIAR. It was impossible to recover the pedigree and origination of five varieties.

Deriving the mechanism by which released varieties were introduced into the national programs, especially those with CGIAR content, is problematic. Centers, national programs and bilateral assistance often promoted the same varieties through different mechanisms. For example, IRRI-developed varieties were tested through the IRTP, the WARDA Coordinated Varietal Trials and also exchanged by IITA breeders with the national program breeders.

Approximately the same number of varieties have been released in the irrigated, rainfed lowland and upland ecologies, but adoption rates differ dramatically (Table 4). The irrigated ecology has the highest adoption rate of improved varieties and has benefitted the greatest from the introduction of materials developed in Asia. This ecology is the most homogenous in the region and, in the case of those irrigation schemes located in the Sahel, the most similar to controlled Asian production systems. In addition, this ecology was the first to take advantage of the Dee Gee WooGen gene responsible for semi-dwarfing and the "Green Revolution" increase in Asian rice productivity. This is the case for in the Senegal River Valley where farmers widely adopted a descendant containing this gene as early as the 1970s. In Mali, the most popular variety cultivated is Kogoni 89-1, a cross of a local cultivar found in the *Office du Niger* with IR34, a second generation descendant of the original "Green Revolution" varieties.

Adoption rates in the uplands are the lowest for all ecologies. In Côte d'Ivoire, approximately 50% of all upland area is planted with introduced varieties, however the two most popular varieties, *Iguape Cateto* and *Morobérekan*, are pureline landraces introduced as early as 1960. When these traditional varieties are removed, the adoption of improved varieties is approximately 8%. Of the 60% of the uplands planted to introduced varieties in Sierra Leone, only 2% is covered by a variety that resulted from a modern cross. The remaining area is planted to purified landraces. Only in Nigeria is there a high percentage of area planted to modern crosses. Approximately 54% of the uplands are planted to modern crosses developed by IITA and the remainder to purified landraces.

Adoption and diffusion patterns for the rainfed lowland ecology are slightly higher than the uplands and very high in Ghana. Until recently, rice was a minor crop in Ghana and when the national agricultural policy began to emphasize rice, the national agricultural research service turned to the CGIAR for its germplasm. In the Ashanti region of Ghana, 40% of farmers plant improved varieties, largely GRUG7, but adoption rates of other inputs, crop management techniques (transplanting) or land improvement investments (bunding) are much lower, at about 20% or less (Dankyi, Anchirinah, & Apau, 1996). Of the 80% of area planted to improved varieties in the rainfed ecology in Ghana, more than half of that area is planted to CGIAR materials.

Extensive evidence exists for the widespread adoption of improved varieties in the mangrove ecology. In the early 1990s, adoption studies indicated a 19% adoption rate for improved varieties in the mangrove swamp areas. Current estimates, derived in this study, indicate that the rate has more than doubled to 39%. In Sierra Leone, much of this increase is attributable to varieties released after the 1992 study and in part to farmer proximity to the Rokupr Station where the varieties were developed. In the deep-water ecology of Mali, the high adoption statistics are linked to the widespread usage of the traditional deep-water Khao Gaew cultivar from Thailand.

Table 4. *Diffusion rates for introduced varieties (% of area cultivated)*

	Total rice area	Ecology				
		Upland	Rainfed lowland	Irrigated lowland	Mangrove	Deep-water
Nigeria	1,784	98[a]	97	100	–	–
Guinea	445	20	55	–	39	–
Côte d'Ivoire	750	50[a]	30	95	–	–
Sierra Leone	289	60[a]	72	57	80	–
Mali	302	10	20	99	–	70
Ghana	96	–	80	65	–	–
Senegal	70	20	30	100	–	–

Source: Survey results.

[a] This rate drops to 54%, 8% and 2% for Nigeria, Côte d'Ivoire and Sierra Leone respectively if purified traditional varieties, introduced in the 1960s and 1970s are excluded from the area tabulations.

At the national level, the overall adoption rates of improved varieties is mixed. Nigeria has the highest rates of varietal adoption. [3] Most of the varieties that are widely cultivated in Nigeria were introduced more than 15 years ago and in the rainfed lowlands, technical change has stagnated since 1974. In the rainfed lowland ecology, nearly 81% of cropped area was planted to varieties developed prior to that date. By contrast, in the upland and irrigated ecologies, 53% and 75% of all area is planted to varieties released during the early 1980s. Only 25%, 3% and 31% of irrigated, rainfed lowland and upland area is planted to varieties released in the 1990s offering casual evidence of the time lag from release to adoption and the pace of varietal turnover.

Widespread varietal diffusion in an heterogeneous environments exists in Côte d'Ivoire and Sierra Leone. The uplands occupy the largest share of rice area in these two countries and both were the target of varietal introduction beginning in 1960s. In Côte d'Ivoire, two robust pure line traditional varieties, one from outside of the region, *Iguape Cateto* and the other from within Côte d'Ivoire, *Moroberekan*, were widely disseminated by agricultural development authorities. Over the past 30 years, these varieties have spread to become the most popular upland varieties in the region and are widely cultivated in both the savanna and forest ecologies. In Sierra Leone, only 2% of upland area planted to released varieties are cultivated to an improved upland cultivar (Jusu, 1999). The remaining area is cultivated with unknown traditional landraces and pureline traditional varieties released by the national program.

4. FINANCIAL IMPACT OF VARIETAL IMPROVEMENT WITH VAGUE DATA

Considerable uncertainty exists in the calculation of the financial impact of varietal improvement in West Africa owing to vague adoption and national rice area data. In order to calculate the regional benefits of varietal improvement under uncertainty, Monte Carlo techniques were used in order to fully exploit variability in the available data and to derive a realistic distribution of probable impact. This approach is similar to that used by Masters, Fisher, and Sidibé (2000) in a country-level setting for irrigated varieties in Senegal.

West Africa produces only two-thirds of consumption requirement and purchases approximately 12% of the volume of world trade in rice. Since the 1970s, growth in rice consumption has outpaced production by 12%. [4] Genetic improvement, in this case, can be analyzed in a small country framework since production increases, due to genetic improvement, do not affect the world price for rice. Under these conditions, the quality-adjusted world price can be taken as a constant and defines the opportunity cost of production resources and consumption (Alston, Norton, & Pardey, 1995). Even under government intervention in the rice market, research benefits will still accrue domestically and the economic surplus captured wholly by producers.

In this framework, the producer surplus gain is measured by a parallel downward vertical shift of the supply function. This study adopts Griliches' (1957) approach to capture the magnitude. Since its original publication, this method, known as the gross annual research benefits (GARB), has been employed by over 90 studies estimating the benefits from a research induced surplus gain (Alston, Chan-Kang, Marra, Pardey, & Wyatt, 2000). Griliches' method is an exact measure of the gains to producer surplus under three conditions: the price elasticity of supply is unitary, the price elasticity of demand is zero, and the incremental costs of adopting the new technology are negligible.

The primary objective of this paper is to estimate the producer surplus gain caused by the research-induced supply shift. This element, commonly referred to as the K factor, was determined for each variety grown in a country and ecology through a series of in-country interviews with rice research and extension workers in 1998. In most cases, adoption rates were estimated by national research and extension authorities using a Delphic procedure rather than through statistical field sampling procedures. Where available, the area estimates and yield effects were corroborated with field observations and research experiments. [5]

In the absence of a comprehensive statistically based adoption and yield study for the countries in the study, adoption rates and yield effects must be viewed as uncertain. [6] Instead of arbitrarily deflating the figures elicited from national authorities, their estimates were considered the upper limit of actual adoption. Through the Delphic procedure, derived during the focus group of national authorities and rice

Table 5. *Distributions and distributional moments used for uncertain parameters*

	Distribution	Minimum (%)	Mean (%)	Maximum (%)	Standard deviation (%)	Variance (%)	Skewness	Kurtosis
Adoption rates (%)								
Nigeria	Beta	30	60	100	0.17	0.03	0.231	2.067
General	Beta	51	80	100	0.11	0.01	−0.304	2.262
FAO area estimates (%)	Normal	82	100	117	0.05	0.002	0.002	2.979

experts, area coverage and yield effects converged to an expected effect. These values are presented for each country, ecology and variety in Table 8. Individual responses were analyzed and provided the mean, median and extremes to construct Beta probability density functions on adoption rates. These probability density distributions were incorporated into the GARB calculation and were sampled simultaneously with replacement using Monte Carlo simulation. Moments of these functions are presented in Table 5.

In addition to adoption rates, FAOSTAT estimates of area under rice cultivation are also uncertain. In this instance, the FAO could be seen as both underestimating areas or overestimating actual rice areas. Therefore, it was assumed that actual rice areas vary by a standard deviation of 5% about the reported FAOSTAT value.

Under the small country assumption, the GARB of the research-induced shift of the supply curve is determined by the proportional yield gain of variety n located in country l and ecology m, multiplied by the opportunity cost of rice for country l. Q is the aggregate rice output in country l and ecology m. The K parameter measures the net reduction in production costs resulting from the technological innovation (Eqn. (1)). It is composed of two elements: the proportional yield gain and the proportional incremental increase in production costs associated with the technology. The K parameter values the yield gain attributable to varietal improvement and assumes that rice yields would not have increased beyond the level of locally available cultivars. [7]

$$\mathrm{GARB} = \sum_{l=1}^{L}\sum_{m=1}^{M}\sum_{n=1}^{N} K_{lmn}P_l Q_{lm} = \sum_{l=1}^{L}\sum_{m=1}^{M}\sum_{n=1}^{N}\left(\frac{\frac{\Delta Y_{lmn}A_{lmn}}{Y_l}}{\varepsilon_l} - \frac{\Delta C_{lmn}A_{lmn}}{Y_l}\right)P_l Q_{lm} \quad (1)$$

In Eqn. (1), ΔY is the yield increase attributable to genetic enhancement, ΔC are incremental costs, A is the area over which the variety was adopted, Y is the aggregate average yield and ε is the price elasticity of supply.

By isolating the impact of genetic enhancement, the sole producer cost of adoption is linked to the replacing existing seed with the enhanced seed. This issue can be considered in two ways. First, without evidence of price differentiation between specific varieties of rice seed, the incremental cost associated with purchasing seed of a new variety is zero, and the term disappears. Second, since rice is a self-pollinating plant that does not lose its vigor from continuous cultivation, many farmers will purchase a small amount of seed, grow the variety, and increase their area to that variety in subsequent seasons. This stock will be retained and grown season to season rather than purchasing purified seed stock annually (Beye, 1999). From a producer perspective, the initial adoption cost is spread across multiple seasons, diffused through areal expansion and may be considered trivial. On a national scale, investment in infrastructure for seed multiplication infrastructure can decrease the time lag between development and widespread adoption. While the cost of these systems are non-trivial, few seed multiplication institutions functioned in West Africa in 1998. This has led to the development of farmer-based seed multiplication systems as an alternative (Beye, 1999).

The short-run elasticity of supply of rice is largely determined by the supply of factors used in rice production. Based upon aggregate data, it is clear that the elasticity of supply in the long run is greater than one. But since GARB measures only an annual benefit and given the fixity of several production factors in the short-run, namely land due to development costs, and inelastic supply of labor in upland areas outside of Nigeria, a unit elasticity of demand is assumed. Although supply of these production factors is inelastic, there is a high degree of substitution between land and labor balancing against inelastic factor supply (Johnson, Jones, Dalton, & Dingkuhn, 1999).

The parameters in Table 5 are sources of potential error in deriving a point estimate of the implicit value of the producers' surplus gain. In order to estimate the probable impact, these parameters were simultaneously sampled with replacement and GARB recalculated until the variance about the expected impact value stabilized. The resulting values and their probability of occurrence are presented in Figure 1.

Overall, the expected cumulative impact of genetic enhancement and transfer contributed US$360 million to the regional rice economy in 1998. In the most conservative case, varietal improvement contributed just US$197 million to the regional economy and at the most optimistic it could have contributed up to US$547 million. There is less than a 10% probability that the actual value is below US$285 million and less than 30% that it is below US$324 million. Figure 1 indicates that there is a high probability that the impact lies between US$290 million and US$407 million and much less certainty that it extends upward, given the high degree of uncertainty adoption rates and FAOSTAT area estimates.

The breakdown and distributional impact upon nations and ecologies, as measured at the median values, is presented in Table 6. Varietal

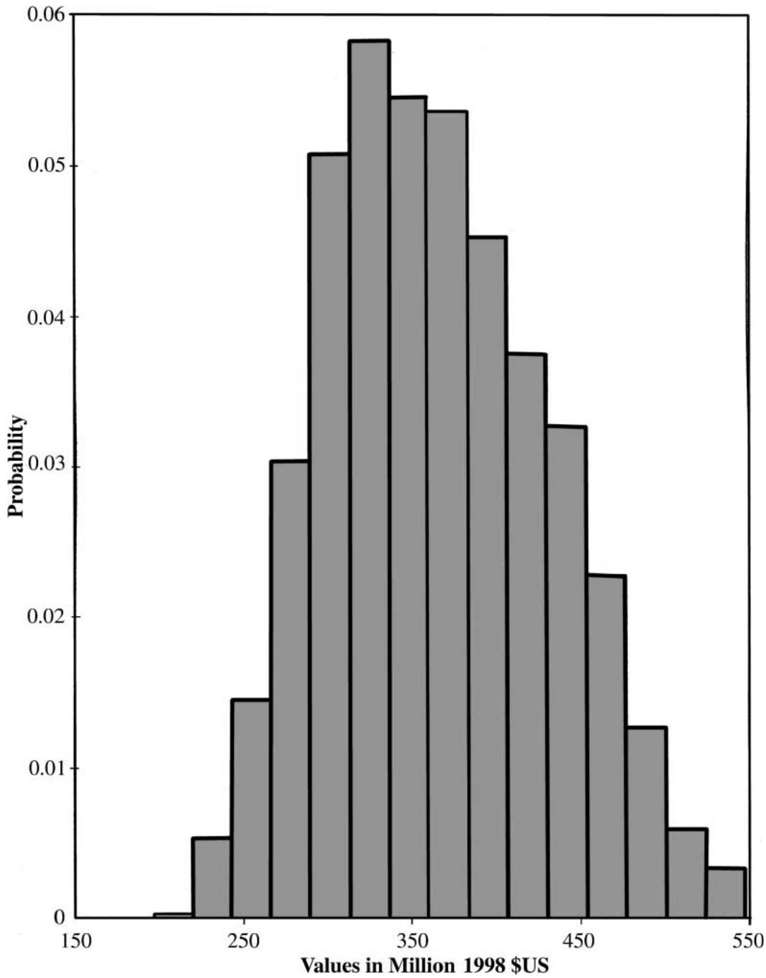

Figure 1. *Probability distribution of the regional GARB from rice varietal enhancement in 1998.*

Table 6. *Median distributional impact of varietal improvement (1998 $US thousands)*

	Rainfed upland	Rainfed lowland	Irrigated lowland	Mangrove swamp	Deep-water floating	Total	Gain/ha (US$)
Nigeria	23,377	141,155	38,166			202,698	112
Guinea	7,221	18,051		3,425		28,696	65
Côte d'Ivoire	12,169	6,249	19,961			38,298	51
Sierra Leone	13,581	10,435	1,141	2,267		27,358	95
Mali	19	244	22,678		6,857	29,129	97
Ghana		30,242	1,566			36,298	330
Senegal	0	381	5,676			6,085	87
Total	56,366	206,341	88,321	5,625	7,870	369,734	96
Gain/ha (US$)	33	161	213	75	25	97	

Source: Authors' calculations based on survey results.

improvement has increased farm revenues, on the average, by US$97 per hectare but much more so in irrigated and rainfed lowland areas. The greatest financial impact has occurred in the irrigated lowlands. On the average, gross revenues per hectare in the irrigated areas have increased US$213 as a result of varietal improvement. [8] This is followed distantly by the rainfed lowland areas at US$161 per hectare, the mangrove swamps (US$75), the uplands (US$33), and in the deep-water floating ecology (US$25). There are very few cases of varieties that are successful in more than one country.

On a national scale, productivity impacts are highly variable but the benefits are much greater for those countries with larger irrigated or rainfed lowland conditions. These results have profound distributional implications for farm households throughout the region insofar that small-scale farmers in the uplands, mangrove swamps and those in highly variable deep-water floating areas, have not benefited to the same degree as those in more favorable rice-growing ecologies. In Côte d'Ivoire, for example, the gain from varietal improvement in the uplands is approximately 16–18% of short-run net revenues per hectare, while in the lowlands it represents about 48% of short-run net revenues (figures calculated from Dalton, 1999).

Productivity gains may be attributed to national programs, CGIAR institutes and traditional varieties from within and outside of the region (Table 7). The most economically important source of genetic enhancement comes from varieties developed by national programs in both Africa and Asia using genetic stock developed by national programs (category 5, NARS Cross-NARS Parent). Of the 103 varieties included in the financial analysis, 38% fall into this class and these varieties account for nearly 40% of the financial impact. Many of the varieties found in this category were varieties developed in Asia for irrigated cultivation and, to a lesser extent, lowland cultivation. In addition, successful varieties developed by Asian and African NARS have also drawn upon CGIAR developed varieties as parents in their crosses (categories 3 and 4).

Over 25% of all varieties currently in use were directly developed by CGIAR institutes including WARDA, IITA and IRRI and these varieties contributed about 29% of the total financial gain. Only one country, Mali, does not use varieties directly developed by the CGIAR

Table 7. *Financial contribution by center content indicators (1998 $US thousands and %)*

Center content indicator	Minimum	Maximum	Median	Share of financial gain (%)	Share of adopted varieties (%)
Center cross-center selection	$53,967	$169,618	$105,684	29.3	25.2
Center cross-NARS selection	$31	$71	$52	0.0	0.9
NARS cross-center parent	$27,224	$71,823	$48,847	13.5	8.7
NARS cross-center ancestor	$4,821	$11,022	$8,025	2.2	4.9
NARS cross-NARS parent	$79,696	$216,425	$142,212	39.5	37.9
Landrace	$24,145	$63,858	$43,391	12.0	20.4
Unknown	$6,718	$18,798	$12,424	3.4	1.9

Source: Authors' calculations based on survey results.

but its most popular irrigated variety uses parental stock developed by IRRI. The total number of CGIAR related varieties climbs to nearly 40% of cultivated area, and contributes over 45% of the research-induced gain when combined with the second, third and fourth categories. This source of impact is distributed widely across all countries and captures the impact of national–international collaborative efforts.

Two cases of impact disproportionate to area coverage emerged in the study. National programs have incorporated CGIAR developed varieties into their breeding programs and developed several highly productive offspring by combining them with varieties resistant to local stress factors (category 3, NARS Cross-Center parent). The best example of this type of relationship occurred in Mali where the resulting variety is the most popular in the irrigated sector and among the most productive in the region. On the other extreme, pureline landraces still account for about 23% of all currently cultivated released varieties, but they proportionately contribute far less of a productivity gain than their area coverage, just 12.0% (category 5, Landrace).

5. CONCLUSIONS

The history of variety improvement in West Africa may be characterized as disjunct, with many actors and overlapping activities often simultaneously pursuing similar objectives. In the 1990s, regional varietal research and improvement was centralized at WARDA and new collaborative mechanisms developed in order to facilitate regional efforts. The resulting impact of the centralization and the renewed collaborative development mechanism may be responsible, in part, for the high numbers of varieties targeted for release during 2000–04. Nonetheless, case studies conducted in several countries over the past eight years indicate that the returns to investment in varietal development have always exceeded 20% annually, and in select cases, upward of 100% per year.

This study found limited financial and human investment in regional varietal improvement. Approximately 36 scientist years in the national programs and 10 additional at WARDA are allocated to rice varietal improvement but financial investment did not exceed US$5.6 million annually in 1998. Despite limited investment in varietal research, 197 varieties have been released over the past 25 years and over one-half have generated sizable gains in rice productivity at the national level.

Using derived adoption estimates, and relying upon historical data on national costs of rice imports as the opportunity cost of forgone production, the study determined that varietal improvement contributed an expected value of US$360 million in 1998 to the regional economy but the amount could be as high as $547 million. Forty percent of the gain is attributable to national agricultural research institutes, 29% to the CGIAR and 16% to collaborative national and international development.

Varietal gains have largely occurred in favorable rice-producing ecologies: the irrigated and rainfed lowlands. According to national research and extension authorities, adoption rates in the irrigated ecologies are close to 100% and about 62% in the rainfed lowlands. Per hectare gains in output are approximately US$233 and US$161 respectively. While the production of improved materials for the mangrove ecology has been impressive, per-hectare productivity gains have been about US$75, largely due to the high productivity of the ecology even when cultivated to traditional varieties. Almost all impact in the floating ecology is due to the transfer of Asian deepwater materials.

By contrast, gains in the uplands, the largest rice-producing ecology, have been much more modest, especially outside of Nigeria. While adoption rates in Nigeria are high, the per-hectare yield gains have been moderate. In other upland rice-producing countries, adoption rates of improved materials do not exceed 30% when introduced traditional varieties are excluded. In the upland rice-growing belt of West Africa—Côte d'Ivoire, Liberia, Sierra Leone, and Guinea—almost all popular released varieties are pureline landraces. While diffusion and adoption of varieties such as LAC 23, *Moroberekan*, *Iguape Cateto*, *Ngovie*, *Ngiema Yakei* and OS6 has been widespread, productivity has increased by only $33 per hectare.

The impact of genetic improvement has occurred disproportionately in the irrigated and rainfed lowland ecologies. West African agricultural research institutes successfully screened Asian rice varieties for useful traits that performed in production systems with water control and adapted these varieties to local conditions. In environments prone to greater biophysical stress, the results have been less pronounced. Almost all area in the uplands is planted to landraces, screened and purified by national agricultural research institutes. Breeding efforts were not successful until the 1990's when international collaboration produced interspecific crosses between African and Asian rices. This research was conducted primarily at WARDA.

These new rices for Africa (acronym NERICA) hold significant potential to improve upland rice productivity. Future impact assessment research should focus on quantifying their effect on farm-level productivity and national rice supply in order to justify the high relative cost of conducting research in international centers and in order to determine whether this ecology, over higher potential lowlands, merits continued research investment. WARDA spends nearly 3.5 times more per scientist than the most expensive NARS in the region.

Second, West African NARS have been very successful in identifying and producing varieties for irrigated and favorable lowland conditions. This success was due in part to the role played by international agricultural research centers in facilitating germplasm exchange and evaluation through international networks. Over 100 new varieties are targeted for release during 2000–04. These are the product of rice research and development conducted in the 1990s and renewed regional germplasm exchange mechanisms. Deriving the impact of these releases and further refinement of applied impact assessment methods to capture network-generated research spillovers will add considerable insight into quantifying and attributing the benefits of modern national and international research organizations.

This paper has highlighted the substantial impact of regional varietal improvement programs by estimating the incremental gain to regional rice production, holding constant crop and resource management interventions. Important additional benefits may be attributed to crop husbandry, fertilizer application and timing recommendations for irrigated and lowland rice. This paper has not attempted to derive any indirect benefits from varietal improvement at the farm or community level. Nevertheless, without regional efforts in varietal improvement, the regional balance of payment deficit for rice imports in 1998 would have been 40% higher or an additional 658,000 hectares of farmland would have needed to be under rice cultivation to maintain consumption levels at their current standard. The regional financial results derived in this study, combined with national case estimates on the returns to rice research, largely discount the claim of limited technological change generated by African public agricultural research.

NOTES

1. Purchasing power parity indices were calculated from data in the 1998–99 and 2000–01 *World Development Reports* (World Bank, 1998, 2000). Since these studies are published biennially, the midpoint of the 1997 and 1999 results was used.

2. Fifty-nine percent of WARDA's annual expenditure is made in $US, 38% in CFA francs and 3% in "other" currencies (WARDA, 1998). These proportions are applied to the total expenditure on varietal improvement and the CFA component is converted to a PPP equivalent using the Côte d'Ivoire conversion factor.

3. Unfortunately, few adoption surveys are available to corroborate high adoption rates and, where available, these studies are usually restricted to limited geographical coverage (Ojehomon *et al.*, 1999). Nonetheless, researchers from IITA have indicated that most farmers claim to know the names of their rice varieties as either FARO or ITA cultivars (Victor Manyong, personal communication). In addition, Nigeria has the longest history of varietal improvement plus an agricultural policy environment which subsidized crop inputs. Regardless of this anecdotal and historical evidence, considerable uncertainty exists on Nigerian adoption rates.

4. Authors' calculation from FAOSTAT data: http://apps.fao.org/.

5. A complete spreadsheet with the area and yield advantage assumptions for each country, ecology and variety is available from the contact author. This is also presented in Table 8.

6. In order to test the reliability of this method, each variety, its yield and its area coverage were summed in order to derive an estimate of total national rice production. These estimates were compared with FAOSTAT estimates of national output using pairwise *T*-tests. No national estimate was rejected at the 90% confidence level.

Table 8. *Economically important varieties used in GARB calculation*

Country and ecology	Variety name (synonym)	Year of release	Area coverage (% of ecology)	Yield advantage (mt/ha)
Nigeria				
Irrigated	FARO 37 (ITA 306)	1986	30	1.0
	FARO 35 (ITA 212)	1986	25	1.0
	FARO 44 (SIPI 692033)	1996	20	0.5
	FARO 50 (ITA 230)	1996	5	1.0
Lowland	FARO 01 (BG79)	1954	15	0.7
	FARO 12	1969	15	0.7
	FARO 15	1974	6	1.2
	FARO 18 (Tjina)	1974	15	0.7
	FARO 35 (ITA 212)	1986	7	1.2
	FARO 37 (ITA 306)	1986	6	1.2
	FARO 44 (SIPI 692033)	1996	2	1.2
	FARO 51 (Cisadane)	1997	1	1.2
	FARO 8 (MAS 2401)	1963	15	0.7
	FARO 9 (SIAM 29)	1963	15	0.7
Upland	EX CHINA	1988	6	0.1
	FARO 43 (ITA 128)	1986	13	0.4
	FARO 48 (ITA 301)	1992	15	0.4
	FARO 11 (OS 6)	1966	25	0.1
	FARO 46 (ITA 150)	1992	26	0.1
Guinea				
Mangrove	WAR 1 (ROK 22)	1993	1	0.6
	WAR 73	1992	1	0.6
	WAR 77	1997	2	0.9
	RD 15	1997	5	0.9
	B 38-D2	1993	10	0.9
	ROK 5	1986	20	0.9
Lowland	CK 21	1996	11	1.5
	CK 211	1989	11	2.0
	CK 30	1995	3	1.5
	CK 4	1988	6	3.0
	CK 43	1998	4	1.0
	CK 73	1995	17	2.0
	CK 92	1989	3	1.5
Upland	CK 12	1994	4	0.5
	CK 5	1995	8	0.7
	CK 7	1995	6	0.6
	CK 8	1994	2	0.4
Côte d'Ivoire				
Irrigated	BG 90-2	1986	1	1.2
	IR 5	1972	2	1.0
	IR 8	1972	2	1.0
	BOUAKE 189	1981	90	1.5
Lowland	GAMBIAKA	1982	20	0.2
	FOSSA	1965	20	0.2
	BOUAKE 189	1981	30	0.4
Upland	IAC 164	1980	1	0.2
	IAC 165	1982	1	0.2
	IRAT 144	1979	1	0.2
	IDSA 6	1982	2	0.2
	MOROBEREKAN	1980	15	0.2
	IGUAPE CATETO	1975	28	0.2

Table 8—*continued*

Country and ecology	Variety name (synonym)	Year of release	Area coverage (% of ecology)	Yield advantage (mt/ha)
Sierra Leone				
Irrigated	ROK 11 (ADNY 2)	1978	2	1.2
	ROK 14 (MANG 2)	1978	20	1.2
Lowland	ROK 24 (Suakoko 8)	1988	35	0.5
	ROK 27 (Warkaiyo)	1988	10	0.5
	ROK 29 (ROYHB 1-1)	1988	2	0.5
	ROK 30 (SI 22-617)	1988	20	0.8
Mangrove	CP 4	1964	5	0.0
	ROHYB 4	1978	5	0.0
	ROK 10 (BL 4-E)	1978	25	0.4
	ROK 22	1988	3	0.6
	ROK 5	1978	38	0.4
	WAR 77-3-2-2	1994	2	0.6
	WAR 81-2-1-2	1994	1	0.6
Upland	ROK 16 (Ngovie)	1988	5	0.2
	ROK 17 (LAC 23)	1988	8	0.3
	ROK 20 (IRAT 161)	1988	2	0.1
	ROK 3 (Ngiema Yakei)	Pre 1970	45	0.4
Mali				
Deep-water floating	D 52-37	1970	2	0.5
	BH 2	1970	3	0.5
	GAMBIAKA	1982	3	0.0
	DM 16	1980	13	0.3
	KHAO GAEW	1962	49	0.4
Irrigated	SEBERANG	1965	5	0.6
	BG 90-2	1986	29	0.8
	KOGONI 89-1	1992	63	1.3
Lowland	GAMBIAKA	1982	5	0.0
	BG 90-2	1986	15	0.1
Upland	DOURADO PRECOCE	1970	10	0.1
Ghana				
Irrigated	GR 22 (SIKAMO)	1997	20	1.4
	GRUG 7	1986	25	1.0
Lowland	GR 17 (IET 2885)	1982	5	1.0
	GR 19 (C168)	1986	5	1.8
	GR 20 (IR 1750-F5-B5)	1986	5	2.0
	GR 21 (TOX 515-19-SLR)	1986	5	2.0
	GR 18 (IR 3273 P339-2)	1983	15	3.0
	GR 22 (SIKAMO)	1997	15	2.5
	GRUG 7 (TOX 725-18-201-1)	1986	15	2.0
Senegal				
Irrigated	SAHEL 201 (BW 292-3)	1994	6	1.6
	SAHEL 202 (ITA 306)	1994	9	1.7
	SAHEL 108 (IR 13240)	1994	19	1.6
	I KONG PAO	1970	20	0.7
	JAYA	1970	40	0.4
Lowland	BG 90-2	1997	2	0.2
	DJ 684D	1972	15	
Upland	DJ 11-509	1997	10	0.0
	DJ 8-341	1982	10	0.0

Source: Survey results.

7. In the case of the Sahelian irrigated schemes, this is the value of the gain over the earliest introduced varieties, in other words, a Type II technological change as described by Byerlee and Moya (1993). In humid areas this gain is in relation to local traditional varieties.

8. This study does not account for the complementary impact of irrigation investment. Water control is a critical input in the realization of genetic potential and we hold that level of control constant in order to isolate the impact of enhancement. Several studies have isolated the impact of irrigation investment across the region.

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