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**Public Expenditures, Private Incentives, and
Technology Adoption**

The Economics of Hybrid Rice in South Asia

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ABSTRACT

The rapid expansion of hybrid rice cultivation in China has contributed significantly to improving food security in the country since the 1980s. However, few other Asian countries have seen similar expansions in hybrid rice cultivation or the associated yield and output gains. This paper examines the technical challenges, market opportunities, and policy constraints related to hybrid rice in South Asia, with specific emphasis on India and Bangladesh. The paper sets the discussion within a novel analytical approach to agricultural science, technology, and innovation that focuses on improving the efficiency with which new technologies are transformed into economically relevant products and services.

Keywords: hybrid rice, agricultural research and development, technological change, innovation, South Asia

JEL codes: Q16, Q18, O31, O33

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1. INTRODUCTION

In 2010, hybrid rice cultivation represented more than half of all area under rice cultivation in China. It has also contributed significantly to increasing national rice yields and output. These contributions have, in turn, contributed to improving food security by feeding an estimated 60 million additional people per year in China. Hybrid rice in China is heralded by many as one of the nation's great agricultural successes (Li, Xin, and Yuan 2010).

Beyond China, studies suggest that hybrid rice can similarly contribute to food security by increasing food staple availability for farm households' own consumption, providing higher yields that increase on-farm incomes, and ensuring supplies of rice that reduce or stabilize prices for both urban and rural food-insecure households (see, for example, Lin and Pingali (1994) and Xie and Hardy (2009)). Moreover, because hybridization provides innovators with the ability to recoup their investments in research, hybrid rice represents a technology platform on which both private-sector scientists and entrepreneurs can make profitable and socially beneficial investments. As such, many policymakers in Asia see hybrid rice as a means of reinvigorating stagnant yield growth in rice, boosting rural incomes, and stimulating private investment in rice improvement.

In reality, however, hybrid rice cultivation accounts for less than 10 percent of area under rice cultivation in Bangladesh, India, Indonesia, and the Philippines and just 10 percent in Vietnam (Table 1.1). Hybrid rice adoption is moving slowly in Asia, particularly in South Asia, where the overall growth in rice yields has been slow in recent decades (Janaiah, Hossain, and Husain 2002). A range of technical challenges, market failures, and policy constraints has limited the development and diffusion of hybrid rice outside of China to date. This paper aims to address these challenges, failures, and constraints and recommend policy solutions to improve the prospects for hybrid rice in South Asia.

A novel way to analyze issues surrounding hybrid rice is to examine the processes behind the product—that is, the factors that are encouraging or inhibiting the discovery, development, and delivery of hybrid rice. This type of analysis requires an integrated framework that opens the *black box* of the research production function. This paper examines the hybrid rice market by focusing on the processes through which new technologies are transformed into economically relevant products. It does so by applying a novel approach to analyzing agricultural science, technology, and innovation policy.

This framework helps identify (1) the key actors, assets, and processes engaged in the production, exchange, and use of new technologies; (2) the actions and interactions that enable these actors to invest in process innovations; and (3) the policies and institutions that influence their actions and interactions. An analysis of the complex systems surrounding hybrid rice (or any other technology) can provide a clear picture of the precise areas in which policy interventions can result in accelerated development and delivery.

This paper proceeds as follows: Section 2 discusses the analytical approach used to better understand science, technology, and innovation policy. Section 3 provides a description of the data and data sources used in this study. Section 4 provides background on hybrid rice and its adoption in Asia. Section 5 discusses the technical, social, economic, and policy dimensions of hybrid rice in South Asia, focusing across the dimensions of scientific discovery, technology development, and product delivery. Section 6 concludes with a set of actionable policy recommendations for further research, development, and delivery of hybrid rice, with particular reference to India and Bangladesh.

Table 1.1—Area under hybrid rice cultivation, selected countries, 1992–2010 (million hectares)

Year	Country (million hectares)					
	China	Bangladesh	India	Indonesia	Philippines	Vietnam
1992	45.4	0.0	0.0	0.0	0.0	0.2
1993	41.6	0.0	0.0	0.0	0.0	0.5
1994	42.1	0.0	0.0	0.0	0.0	0.9
1995	43.3	0.0	0.1	0.0	0.0	1.1
1996	46.1	0.0	0.2	0.0	0.0	1.8
1997	47.7	0.0	0.3	0.0	0.0	2.6
1998	47.4	0.0	0.4	0.0	0.0	2.7
1999	44.0	0.0	0.4	0.0	0.0	3.0
2000	45.3	0.0	0.4	0.0	0.0	5.7
2001	49.6	0.0	0.4	0.0	0.3	6.4
2002	50.2	0.2	0.5	0.0	1.2	6.7
2003	49.4	0.3	0.7	0.0	3.3	8.1
2004	51.2	0.8	1.4	0.0	3.2	7.7
2005	51.4	1.9	1.8	0.0	4.6	9.0
2006	52.1	3.7	2.3	0.2	8.8	8.0
2007	50.3	9.5	2.5	2.4	4.7	8.5
2008	54.1	8.9	3.2	2.6	4.5	8.8
2009	52.1	7.5	3.7	5.2	4.3	9.4
2010	51.8	6.8	4.6	4.9	4.6	10.0

Source: Authors' creation, based on figures on area under rice cultivation from IRRI (2012b) and area under hybrid rice cultivation from Achim Doberman and Fangming Xie, International Rice Research Center (pers. comm., 2011).

Note: Estimates of area cultivated under hybrid rice vary in all countries listed here, depending on source, year, and data collection process.

2. CONCEPTUAL FRAMEWORK

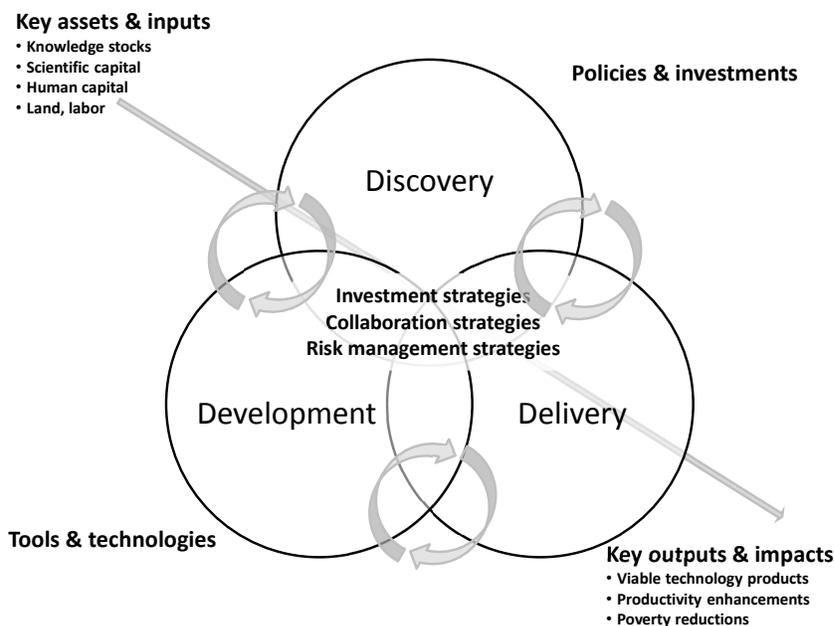
There are obvious challenges in transforming a technology such as hybrid rice into an economically relevant production factor. One way of addressing these challenges is to develop a better understanding of the complexity in how factors of technology production—scientific capital, technical know-how, breeding materials, and seed production systems—are translated into real outputs, such as marketable quantities of hybrid rice seed or hybrid rice as a tradable commodity itself.

One way of better understanding these issues is to examine the processes that translate science into viable technologies and, ultimately, into commercial products, as well as the incentives that motivate individuals, firms, and governments to invest in these processes. This type of examination requires shifting our analytical emphasis to the question of how, rather than why, science, technology, and innovation (ST&I) policies and investments should be made, or focusing on systemic complexity and knowledge gaps rather than on cost–benefit analysis.

The ST&I framework used here answers the *how* question by emphasizing the roles played by diverse actors in the production, exchange, and use of ST&I products and processes; the institutions and incentives that condition these actors’ actions and interactions; and the precise policy interventions that are most likely to result in welfare-improving outcomes. It does so by focusing on the analysis of optimal investment, collaboration, and risk management strategies that define the critical decisionmaking points for investment in agricultural ST&I.

The framework examines decision points at three stages of analysis—discovery, development, and delivery (Figure 2.1). During this process, knowledge, scientific, human, and productive capital are all transformed into marketable outputs and measureable inputs through an iterative process of discovery, development, and delivery. *Discovery* describes the investment, collaboration, and risk management strategies related to scientific and technical inquiry at the earliest phase of innovation. *Development* describes the translation of science into technology and the market opportunities, regulatory hurdles, and other constraints associated with this process. *Delivery* refers to the adoption and uptake of a technology through various market and nonmarket distribution channels that are influenced by the economic behavior of individuals, firms, and governments.

Figure 2.1—From discovery to delivery: The ST&I framework



Source: Authors’ creation.

At the nexus of discovery, development, and delivery is a series of institutional and industrial strategies involving investments, collaborations, and risk management. This framework illustrates the discovery, development, and delivery process as an iterative process of learning that results in innovative technologies (for example, interactions between discovery and delivery facilitates demand-driven innovations), innovative processes (for example, interactions between discovery and development facilitate new methods and approaches for streamlining the research and development pipeline), and innovative dissemination (for example, interactions between development and delivery facilitate new methods for transmitting information about the technologies or for transmitting the technologies themselves).

Table 2.1 summarizes these three stages, highlighting the clearly defined investment, collaboration, and risk management strategies that innovators and policymakers must address when making critical decisions and pursuing specific actions. Where information and analysis are limited and where public policies give little guidance in steering decisions and actions to optimal outcomes, innovators face greater levels of uncertainty. This uncertainty necessarily reduces the probabilities that a given technological opportunity will enhance productivity, reduce poverty, or promote equity in developing-country agriculture. Efforts to bridge this information gap and design farsighted public policies are an essential contribution of any analytical work on ST&I.

Table 2.1—Key stages and strategies in an ST&I framework

Key Stages	Product Discovery	Product Development	Product Delivery
Key function	Basic research and upstream science	Applied/adaptive research and product introduction	Product marketing and distribution
Investment strategy	Identify or acquire relevant research assets; Identify research (technical) strategy	Transform research into a commercial product; Develop production systems and business models for commercialization	Develop marketing strategies and distribution systems
Collaboration strategy	Identify and leverage research networks and partnerships; Review intellectual property (IP) rights needs to identify licensing or collaboration priorities	Identify and leverage product development networks and partnerships	Manage in-house versus outsourced production; Identify marketing partners and partnering strategies
Risk management strategy	Identify regulatory issues associated with the research	Identify market risk issues associated with the product; Collect and manage environmental safety, human safety, and other regulatory data	Manage production and product safety; Manage market risk; Identify industry structure and concentration issues; Ensure IP protection and product stewardship

Source: Authors' creation.

Necessarily, these differentiated stages of discovery, development, and delivery are based on overlaps and interactions, a reality that draws attention to the fact that most innovative opportunities cannot be exploited simply on the basis of a linear process that moves from upstream science into downstream application. Instead, the process begins with a widely defined set of assets: explicit inputs, such as known stocks of scientific capital, other forms of capital, land, and labor, as well as more implicit or tacit inputs, such as scientific experience, indigenous knowledge, and managerial capacity. The application of these assets to a particular problem or production constraint leads to a nonlinear progression influenced by (1) the availability of appropriate tools and technologies (the state of the art); (2) the capacity of agents to iterate, learn, and innovate through this progression (innovative capabilities); and (3) the existence of appropriate policies and investments in support of ST&I (the enabling environment).

In short, although ST&I can contribute to solving problems in developing-country agriculture, the solutions require more than just good science. They also require the right tools and technologies plus the right policies and investments.

3. DATA AND DATA SOURCES

This paper relies mainly on publicly available data on rice research, cultivation, and production garnered from government and private-sector sources. Data and analysis were extracted from a range of sources, including peer-reviewed journal articles, government statistical reports, private databases, and documents from industry sources. Key sources are as follows.

Key Informant Interviews

Information was gathered from a series of unstructured interviews held from 2008 to 2010 in several locations across India. Interviews were conducted with people knowledgeable about India's seed and agricultural biotechnology industries, including corporate decisionmakers, private-sector researchers, public regulators, social science researchers, policy analysts, and biophysical scientists working in both public and private research units. Table 3.1 provides a breakdown of key informants by sector. Questions covered during the interviews were related to seed and agricultural biotechnology market opportunities in India (with specific reference to rice, wheat, and maize), research and development (R&D) investment strategies and constraints, product delivery strategies and constraints, intellectual property rights (IPRs), technology forecasts and opportunities, and regulatory issues.

Table 3.1—Key informants interviewed, 2008–2010

Affiliation	Number
Private sector (managers, researchers, others) ^a	36
Public sector (regulators, researchers, others) ^b	35
Donors, nongovernmental organizations, charitable foundations, and others ^c	6
Total	77

Source: Authors' creation.

Notes: ^a Includes representatives of industry associations.

^b Includes researchers from the Consultative Group on International Agricultural Research.

^c Includes representatives of donor agencies, international organizations, charitable foundations, and nongovernmental organizations.

Francis Kanoi Marketing Research Group survey

The Francis Kanoi Marketing Research Group conducted a survey-based study on rice cultivation and the rice seed market during 2008–2009 in India. The survey's main objectives were to estimate the demand potential for rice seed, identify various seed sources and their respective market shares, estimate the costs of cultivation of rice across various states and production zones, and estimate the market share of various companies in the hybrid rice seed market. The survey covered 11,076 rice farmers across 139 districts (districts with more than 30,000 hectares under rice cultivation) in the 16 major rice-growing states of India for the 2008–2009 agricultural season.

Bangladesh Integrated Household Survey

The Bangladesh Integrated Household Survey (BIHS) was conducted by the International Food Policy Research Institute in late 2011 as part of the Bangladesh Policy Research and Strategy Support Program (PRSSP). The BIHS contains data on 5,503 households drawn from 64 districts in the seven primary divisions and is representative at both the national and divisional levels. The survey covers topics that are standard to most income and expenditure surveys in developing countries, as well as topics related to agricultural production, plot utilization, input use, and postharvest management.

Cereal Systems Initiative for South Asia Baseline Household Survey

The Cereal Systems Initiative for South Asia (CSISA) baseline household survey was conducted by researchers from the International Rice Research Institute (IRRI) and the International Maize and Wheat Improvement Center (CIMMYT) during the second half of 2010 and the first quarter of 2011. The survey sample was generated based on a stratified random sampling approach within the domains of the eight innovation and delivery hubs established as part of the initiative (five in India, two in Bangladesh, and one in the Terai region of Nepal). Within each hub domain, three districts were randomly selected. From each of these districts, three blocks (or subdistricts) were randomly selected. From within each block, two villages were selected—one a beneficiary of CSISA interventions and one not receiving such interventions. From within each village, 18 households were randomly selected from village rosters for inclusion in the survey. In all, the survey contains information on 2,627 households. Although not nationally representative, the sampling strategy is such that the samples are intended to be representative of the villages included in the hub domains. The survey contains comprehensive information on many aspects of agricultural production and technological adoption. The data and information presented in this paper are drawn primarily from a sample of districts in which CSISA operates in Bihar, eastern Uttar Pradesh, Haryana, and Tamil Nadu.

4. BACKGROUND

Hybrid vigor, or heterosis, is the increase in yield, uniformity, or vigor of cultivated plants that results from genetic contributions derived from the crossing of distinct parental lines. Its economic value lies in the fact that yield gains conferred by heterosis decline dramatically after the first generation of seed (F1), thus compelling farmers to purchase new F1 seed each season if they want to continually realize these yield gains. This contrasts with conventional open pollinated varieties (OPVs) or inbred varieties (for rice), in which harvested grains can be stored and used as seeds in the following year.

This unique characteristic has been a driving factor behind investment in crop improvement for maize and several other crops.¹ Public research on maize hybridization in the early twentieth century in the United States contributed to the development of a lucrative seed industry during the 1930s. This development saw the entry of many small and medium-sized seed companies breeding and marketing hybrid maize seed to farmers. By the 1960s, almost all maize cultivated in the United States was grown from hybrid seed. Annually, maize receives more than US\$1 billion in private R&D investment in the United States—more investment than any other crop—owing largely to the incentives that hybridization provides to private breeders (see Fernandez-Cornejo 2004; Fuglie et al. 1996).²

Beyond the United States, hybrid maize cultivation has spread throughout the world, including into developing countries in Latin America, Sub-Saharan Africa, and Asia (Morris 1998). Hybrids of other crops, such as sorghum, pearl millet, cotton, and many vegetable crops, have also made similar inroads in developing countries (see, for example, Pray and Nagarajan 2010). Hybrid rice got its start in India in 1954, when heterosis in rice was first documented by S. Sampath and H. K. Mohanty at the Central Rice Research Institute, Cuttack, in the Indian state of Orissa (see Sampath and Mohanty (1954)).

Despite the lucrative benefits of hybridization to both firms and farmers, substantial criticisms and concerns exist over their place in developing-country agriculture. First is the concern that seasonal or annual purchases of hybrid seed are too costly for many resource-poor, small-scale farmers in developing countries (Kuyek 2000). Several points are worth noting regarding this contention. One is that much evidence suggests that purchasing seed—both OPV and hybrid—is a fairly common practice among rice farmers in South Asia (Table 4.1), despite conventional narratives that argue otherwise. Data from the BIHS suggest that although almost 45 percent of farming households in Bangladesh use saved seed, more than 75 percent purchase rice seed from private sources. This suggests that many farming households (more than 25 percent) use both saved seed and purchased seed, and that a large percentage of farming households purchase rice seed from private sources. A related point is that although seed saving is an important crop management and livelihood strategy among the poor, it necessarily limits their access to technological improvements embodied in seed. Commercial seed markets are one among several mechanisms through which farmers can access these technological improvements—access that they might forgo if they were to depend solely on own-seed savings or exchanges with neighbors. A further point worth noting is that although hybrid rice seed is indeed significantly costlier than OPV rice seed (approximately 10 times the price), these costs are partly defrayed by a lower seeding rate.³

¹ The first experiments that demonstrated the influence of inbreeding and outcrossing on vigor in maize were conducted in 1906 by George H. Schull, a scientist for the Carnegie Institution who worked at its Station for Experimental Evolution in Cold Spring Harbor, N.Y. Schull later proposed the term heterosis to describe hybrid vigor. In the mid-1910s, Donald F. Jones, at the Connecticut Agricultural Experiment Station in New Haven, Conn., experimented with maize hybrids that could be produced on a commercial basis. This led to the release of the first commercial double-cross hybrid in 1921, a timely technology contribution to reversing stagnant maize yields in the United States (Fernandez-Cornejo 2004; USDA 1962).

² All dollars mentioned in this report refer to U.S. dollars.

³ Recommended seeding rates ranging from 15–30 kg/ha for transplanted hybrid rice, depending on agroecological conditions and other management practices. These seeding rates are generally lower than rates for inbred rice. See Virmani, Siddiq, and Muralidharan (1998) and Xie and Hardy (2009) for further discussion.

Table 4.1—Seed replacement rates for various crops in selected South Asian countries (percentage)

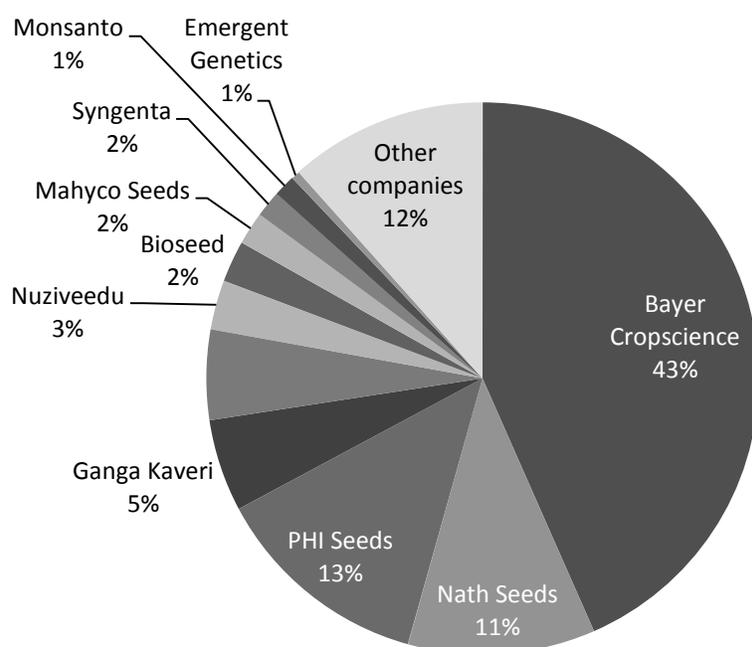
Crop	India, 2007 (%)	Bangladesh, 2007 (%)	Nepal, 2002 (%)	Pakistan, 2007–08 (%)
Wheat	25.23	26.46	28.5	17
Rice	25.87	24.74	11.1	34
Maize	44.24	97.97	9.2	32
Sorghum	19.87			
Millet	48.47			
Soybean	33.39			
Sunflower	62.88			39
Cotton	15.30			48

Sources: Seednet (2007) for India; BSGDMA (2007) for Bangladesh; ANZDEC Limited (2002) for Nepal; and Seed Association of Pakistan (2012) for Pakistan.

Note: Includes seed replacement rates for both open pollinated varieties and hybrids where applicable, such as for rice, maize, sorghum, millet, sunflower, and cotton.

Second is the concern that hybridization concentrates market power in the hands of a few companies that are able to breed and market superior hybrids. This concern invokes the notion of *seed security*, or that farmer and national dependence on market forces to supply seed increases smallholders' and national vulnerability to monopolistic pricing or other predatory practices by multinational seed companies. Although compelling evidence suggests that some seed markets are highly concentrated in some countries and that corporate pricing strategies may be welfare reducing for farmers in certain instances, the question of market power is essentially an empirical one, requiring careful and context-specific analysis. Even in a country like India, which has a relatively large number of seed companies in the market, a large share of the hybrid seed market is dominated by a small handful of firms. As Figure 4.1 illustrates, more than 75 percent of the total hybrid market (by value) was captured by just five firms.

Figure 4.1—Structure of India's hybrid seed market in India by value, 2008–2009.



Source: Authors' calculations based on data from Francis Kanoi Marketing Research (2009).

Third is the concern that hybridization leads to greater risk in the form of (1) lower in situ genetic diversity and greater susceptibility to pests and disease and (2) fewer management alternatives to cope with weather-related production risks, particularly for smallholders with limited access to credit, insurance, and other services that help manage risk. Again, the extent to which these factors are significant concerns is largely an empirical question that depends on context and situation.

In short, despite criticisms of commercially marketed hybrid seeds for smallholders, the welfare trade-off between farmer-saved seed and farmer-purchased seed, as well as the externalities associated with lost biodiversity, are not as clear-cut as suggested. The specific opportunities, challenges, and risks associated with rice hybrids are discussed in more detail throughout this paper.

Hybrid Rice in China and Southeast Asia

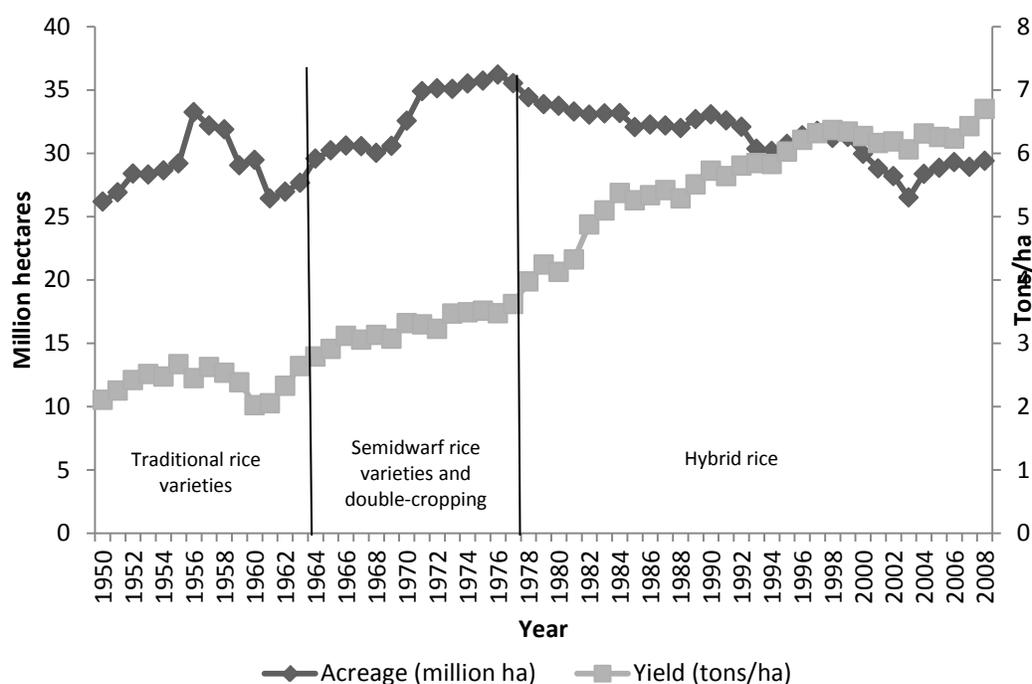
Concerted R&D investment in hybrid rice began in 1964 in Hunan, China, a full decade after heterosis in rice had been discovered (Li, Xin, and Yuan 2009). China's substantial investments in hybrid rice focused on the significant technical challenges associated with hybridization: finding sterile lines that could be crossed with fertile lines to generate the stable expression of heterosis in an otherwise self-pollinating crop.⁴

By the mid-1970s, scientists had largely succeeded in developing hybrids and seed production systems that led to large-scale dissemination among small-scale farmers in China beginning in the early 1980s. China's long-term investment in the development of rice hybridization systems, hybrid rice breeding, and hybrid rice seed production resulted in rice hybrids that outyield traditional and semidwarf rice varieties, while also providing adequate levels of stress tolerance and responsiveness to inputs. In the ensuing years, researchers were also able to improve grain quality to a point that was more acceptable to consumers than earlier hybrid rice releases.

As of 2010, hybrid rice accounted for more than 50 percent (and as high as 63 percent, depending on the source of the estimate) of all land under rice cultivation in China, yielding between 15 and 31 percent more than other cultivated rice varieties. The dissemination of hybrid rice between 1978 and 2008 contributed to a 68.4 percent increase in national rice yields, raising average yields from 4.0 to 6.7 tons per hectare during this period (Figure 4.2). Total national rice production similarly increased by 44 percent, from 136.7 million tons in 1978 to 197 million tons in 2008 (Li, Xin, and Yuan 2009).

⁴ Although cross-pollination or outcrossing does occur in cultivated rice, it occurs at low levels, averaging at around 5 percent. See Virmani (1994).

Figure 4.2—Rice cultivation and yields in China, 1950–2008



Source: Li, Xin, and Yuan (2009), based on data from the China Ministry of Agriculture and International Rice Research Institute.

The yield advantages of hybrid rice have also allowed China to reduce the amount of land allocated to rice cultivation. Between 1978 and 2008, the total area under rice cultivation in China decreased from an estimated 34.4 million hectares to 29.4 million hectares, a 14.5 percent decrease (Li, Xin, and Yuan 2009). This decrease allowed for diversification of agricultural production into other crops, such as high-value fruits and vegetables, as well as the conversion of farmland into urban and industrial use.

Despite initially low rates of returns to hybrid rice cultivation reported by Lin (1991), other studies have found high returns owing to a combination of higher yields and lower labor and nonlabor input requirements (Lin and Pingali 1994; He and Flinn 1989; He et al. 1988; Tao 1987). These returns likely encouraged the rapid expansion of hybrid rice cultivation across temperate and tropical rice-growing provinces in China. The expansion may also be a result of the government’s commitment to hybrid rice research, its aggressive campaign to promote hybrid rice among farmers, its support for the emergence of a vibrant seed industry to deliver seed to farmers, and its introduction of production incentives that emerged through land tenure reforms of the 1980s (see, for example, Lin 1991). In short, China’s success in promoting hybrid rice is the result of a long-term investment program and policy environment that engaged both the public and private sectors with farmers.

Without going into too much detail and diverting attention from a more detailed analysis of trends in South Asia, it is sufficient to say that hybrid rice in the rest of Asia has shown mixed performance. As shown in a nonexhaustive review of cost and returns studies on hybrid rice (Table 4.2), there is much variability in performance between countries. Reported yield improvements in Vietnam are negligible in Vietnam, but higher in the Philippines, while net returns are reported as positive in both countries. That said, the comparative returns estimated by the studies shown in Table 4.2 should be considered cautiously due to methodological limitations. Most of these studies do not provide effective strategies to address sample selection biases associated with unobservable differences between households cultivating hybrid and nonhybrid rice. Efforts to explain the returns to hybrid rice adoption require more careful

consideration of the heterogeneity of the farm households and the production factors at their disposal, the endogenous relationships between technology adoption and these same factors, and the external validity of results across diverse environments.⁵

Table 4.2—Costs and returns to hybrid and inbred rice, selected Asian countries and years

Country	Yield (t/ha)			Total Cost (US\$/ha)			Net Returns (US\$/ha)		
	Hybrid	Inbred	% Diff.	Hybrid	Inbred	% Diff.	Hybrid	Inbred	% Diff.
Bangladesh									
2004	7.3	5.9	23.7	559	507	10.3	360 ^c	279 ^c	29.0
2005	8.2	6.6	24.2	547	524	4.4	604 ^c	412 ^c	47.0
2007 ^a	7.3	6.0	22.0	717	727	-1.5	431 ^c	197 ^c	119
2007 ^b	7.3	5.4	35.0	717	696	3.0	431 ^c	194 ^c	123
Vietnam									
2006 WS	5.4	5.2	4	NA	NA	NA	+15 ^d	NA	NA
2007 DS	6.4	6.2	3	NA	NA	NA	+28 ^d	NA	NA
Philippines									
2003 DS	5.7	5.0	14.0	NA	NA	NA	NA	NA	27.2
2003 WS	5.5	5.1	7.8	NA	NA	NA	NA	NA	6.4
2004 DS	5.3	4.8	10.4	NA	NA	NA	NA	NA	26.0
India									
1997–98	6.9	5.9	16.0	283	239	19.0	475	500	-5.0
2000–01	6.8	6.0	13.3	377	320	17.8	468	549	-14.8

Sources: Adapted from Pandey and Bhandari (2008); for Bangladesh: Azad, Mustafi, and Hossain (2008) and Hossain (2008); Vien and Nga (2009) for Vietnam; Sebastian and Bordey (2005) and David (2006) for Philippines; Janaiah and Hossain (2003) and authors' calculation based on Francis Kanoi Marketing Research (2009) for India.

Notes: ^a Against inbred variety BRRI 29.

^b Against inbred variety BRRI 28.

^c Net return calculation includes straw value for Bangladesh.

^d Net return calculations against inbred varieties Khang Dan, Bac Thom 7, and Nep 97.

NA = not applicable; WS = west season; DS = dry season.

Hybrid Rice in South Asia

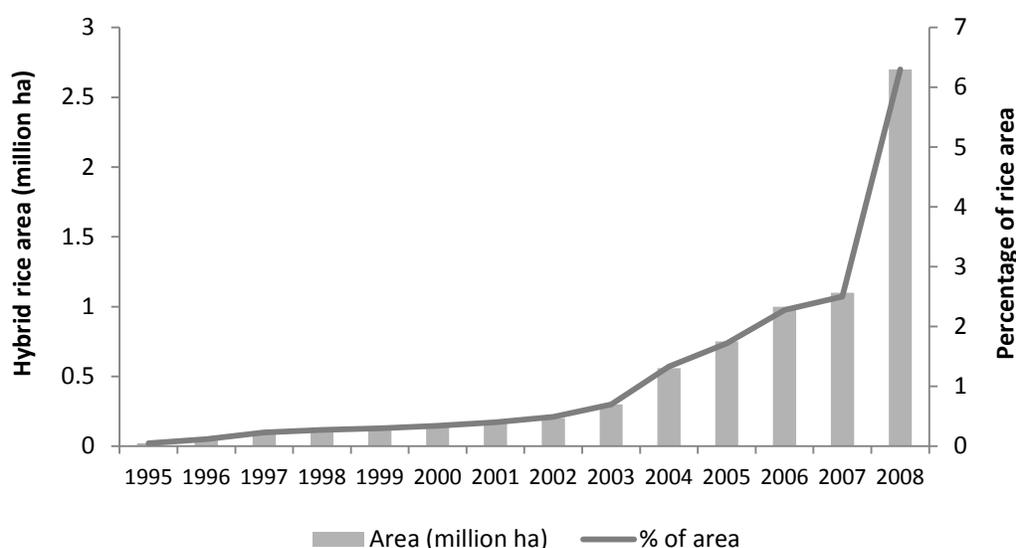
Hybrid rice development in South Asia has been hampered by several nontrivial scientific and technical challenges. From the outset, public- and private-sector researchers in South Asia have been working with a narrow germplasm base that poses significant constraints on producing marketable hybrids with the yield advantages preferred by farmers and the grain qualities preferred by consumers (Janaiah 2002; Janaiah, Hossain, and Husain 2002; Janaiah and Hossain 2003, 2005). An additional challenge has been the multiplication of hybrid rice seed in significant levels of quality and quantity (Xie and Hardy 2009). Although solutions to many of these technical challenges have emerged in recent years, their initial persistence gave hybrid rice a rocky start in South Asia. To better appreciate how the ST&I framework applies to the development of South Asia's hybrid rice market, it is first worthwhile considering the context and experiences of India and Bangladesh—the two most populous countries in South Asia and two countries that provide among the greatest potential benefits for increased penetration of hybrids.

⁵ See Feder, Just, and Zilberman (1985) and Jack (2011) for a review.

The Indian Experience

Systematic research on hybrid rice in India only began in 1989 under a relatively small program of the Indian Council of Agricultural Research (ICAR), focusing on hybrids for irrigated cultivation (Janaiah 2002). Subsequent research programs, totaling approximately \$8 million, have been funded by the United Nations Industrial Development Organization (UNIDO) and Food and Agriculture Organization (FAO) (1991–96 and 1999–2001), the Mahyco Research Foundation (renamed the Barwale Foundation since 2005) (1997–2000), the Asian Development Bank (ADB) and IRRI (1999–2000), and the National Agricultural Technology Project (funded by the World Bank) and India’s Ministry of Agriculture (2003–08). Despite these investments, the development and delivery of hybrid rice in India have faced several challenges that have delayed the government’s goal of introducing hybrid rice on 25 percent of all cultivated rice area by 2015. As of 2008–09, hybrid rice represented an estimated 6 percent of India’s 44 million hectares under rice cultivation (Figure 4.3), though the area under cultivation increased significantly from 2007 to 2008.

Figure 4.3—Area under hybrid rice cultivation in India, 1995–2008



Source: Authors’ calculations based on Baig (2009) and Francis Kanoi Marketing Research (2009).

Farmers’ concerns about the inferior grain quality, low market price, susceptibility to biotic stress, and poor yield increases conferred by hybrids discouraged many early adopters in the intensive rice–rice systems of south India and the rice–wheat systems of northwestern India in the early to mid-1990s. Janaiah (2000, 2002) provided some of the earliest evidence on the economics of hybrid rice adoption in India with survey data from small samples of households in the states of Andhra Pradesh, Karnataka, Tamil Nadu, Haryana, Orissa (now known as Odisha), Punjab, and West Bengal. Although the sampling frames are insufficiently representative and the methods do not sufficiently address the bias issues mentioned earlier, these early observations do provide some useful insights on those few households cultivating first-generation hybrids in India. Janaiah (2000, 2002) reported that poor quality seed, variable yields, poor adaptation to certain agroecological conditions, susceptibility to pest and disease pressures, and low prices received for inferior quality grain were to blame for poor adoption rates.⁶ In general, he concluded that hybrids available in the market at that time were not profitable for farmers in India.

⁶ Janaiah’s observations of yield gains in the remaining three states—ranging from 19 percent in Karnataka and 53 percent in West Bengal—are notable but also subject to issues of sample bias.

Subsequent efforts to improve breeding and promote hybrids in other parts of India met with mixed outcomes. Despite the breeding improvements and promotional efforts—and, in some places, up to 50 percent subsidies on seed price—studies reported mixed outcomes from hybrid rice cultivation in 2000–01. Chengappa, Janaiah and Gowda (2003), Janaiah (2003), and Ramasamy et al. (2003) found that even where hybrids were marginally higher yielding than popular inbred varieties (due largely to better-quality seed, higher fertilizer responses, and better crop management), farmers faced additional challenges that reduced profitability. The higher costs of seed and fertilizer inputs, coupled with the lower market price for hybrid grain due to poor quality and poor rice head recovery during milling, meant that the net returns to hybrid rice were frequently lower than for varieties. Ultimately, farmers abandoning hybrid rice cited a long list of reasons for their discontinued use, including poor grain quality, low market price, high seed cost, nonavailability of quality seeds, susceptibility to pests and diseases, low head-rice recovery, and chaffy or sterile grains. Despite all this, the proportion of area under hybrid rice has grown at a rate of about 40 percent per year since 2005, albeit from a low base (Figure 4.3). This has occurred most markedly in four northern and eastern states—Jharkhand, Bihar, Uttar Pradesh, and Uttarakhand—where rice yields are low relative to the national average. In these four states, private hybrids account for more than 95 percent of area under hybrid rice cultivation (Baig 2009; Francis Kanoi Marketing Research 2009; Viraktamath and Nirmala 2008). Currently, 80 percent of the total hybrid rice area in India is cultivated in Jharkhand, Bihar, Uttar Pradesh, and Chhattisgarh, with smaller areas under hybrid cultivation in Madhya Pradesh, Assam, Punjab, and Haryana (Viraktamath 2011).

Yet hybrid rice is still characterized by a low rate of adoption. According to data from the Francis Kanoi Marketing Research (2009) survey, only 6.3 percent of farmers sampled were planting hybrid rice in 2008–09, accounting for only 6.2 percent of total area under rice cultivation. Still, the same survey reported that 24 percent of surveyed rice farmers in Bihar and 15 percent in Uttar Pradesh have tried cultivating hybrid rice at some point in the past. Likewise, according to data from the CSISA baseline survey, 53 percent of surveyed farmers in selected districts of Bihar have cultivated hybrid rice, 15 percent in selected districts of eastern Uttar Pradesh, and 26 percent across the entire sample of selected districts and states.⁷

A relatively new study by Janaiah (2010) provides some insight on adoption determinants with data from a 2008 survey of rice farmers in Chhattisgarh, Uttar Pradesh, and Haryana. In the Janaiah (2010) sample, hybrids still demonstrate a significant (30 percent) yield gain and profitability over inbred varieties in the two rainfed eastern states (Chhattisgarh and Uttar Pradesh) and are generally equal in yield and profitability in the irrigated northwestern state (Haryana). An important change, however, is that farmers generally do not perceive grain quality as a serious issue as compared with survey findings on the previous generation of hybrid rice a decade earlier.

Data from the CSISA baseline survey suggest that a wide variety of issues are influencing hybrid rice adoption in India. In addition to information constraints and ambiguity, which constrain farmers' understanding of varietal alternatives, concerns about low yields; poor seed quality (such as concerns over dealers mixing high-quality seed with poor-quality seed); lower profitability (primarily resulting from lower output prices rather than the higher seed price); and susceptibility to pests, diseases, and weeds have led farmers not to adopt hybrids. Even among those farmers who, at some point or another, have adopted hybrids, poor seed quality and low yields have contributed to the discontinued use of hybrid rice within the Indian sample covered in the CSISA baseline survey (Table 4.3).

⁷ Given the high rates of hybrid rice adoption reported in the CSISA baseline survey relative to other sources, it is worth noting possible issues relating to data quality and accuracy. One issue is that although the CSISA baseline survey specifically asked farmers about their familiarity and experience with hybrid rice, it is possible that farmers, enumerators, or both did not accurately distinguish among hybrid rice, high-yielding (modern inbred) rice varieties, and traditional (land race) rice varieties. Alternatively, it is possible that the districts covered by the CSISA baseline survey were characterized by progressive farmers or more vibrant seed and input markets relative to all-India figures, thus resulting in high rates of hybrid adoption. That said, the CSISA baseline survey data are not implausible in light of state-level adoption rates reported by Francis Kanoi Marketing Research (2009).

Table 4.3—Constraints to adoption and cited reasons for discontinued use of hybrid rice among CSISA hub domains in India (percentage of qualifying respondents)

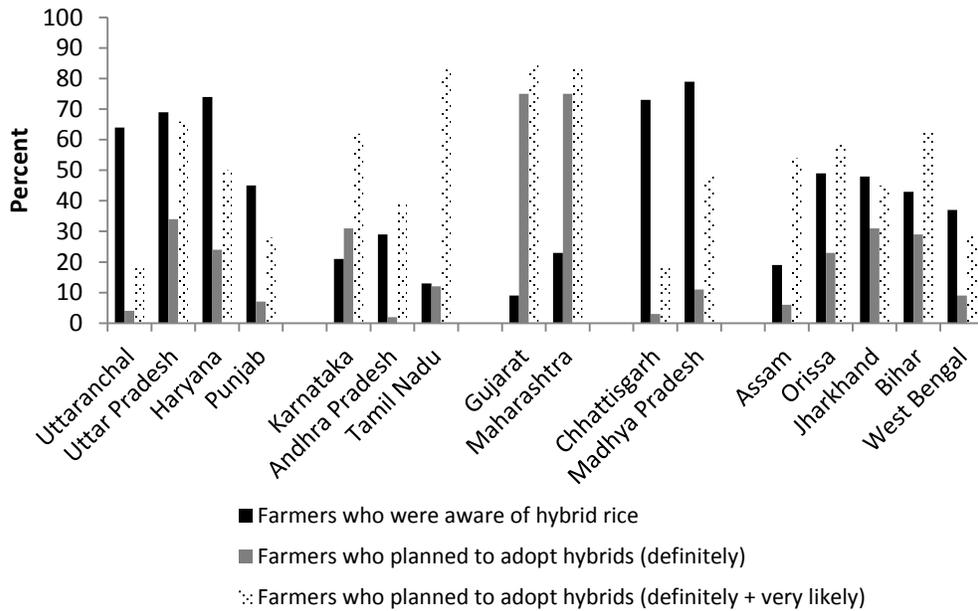
Constraint	Never Adopted (%)	Discontinued (%)
Capital constraints	0.76	1.91
Information constraints	12.12	7.01
Labor constraints	0.38	1.27
Land constraints	1.52	5.73
Low yield	16.67	26.11
More costly/Less profitable	14.39	8.92
Not popular	17.42	12.10
Others	2.27	3.82
Pests/Diseases/Weeds	13.26	15.92
Poor grain quality	3.79	1.27
Poor seed quality	15.91	15.92
Risk aversion	0.76	0.00
Unsuitable	0.76	0.00

Source: Authors' creation based on data from CSISA (2011).

As with earlier efforts to promote hybrid adoption, recent efforts in these areas have relied, to some degree, on government subsidies, though in many cases only on limited volumes of hybrid seed. For example, Uttarakhand has a strategy supporting the increased distribution of hybrid rice seed that provides farmers with either 2,000 rupees (Rs.) per quintal (100 kg) of seed or 50 percent of the cost, whichever is less. In Uttar Pradesh, the government instituted a 25 percent subsidy on hybrid seeds in 2011 in an effort to increase the total area under hybrids by 150,000 hectares per year (Dwivedi 2011). It remains to be seen whether—or to what extent—these subsidies will crowd out private purchases or whether the penetration and growth of hybrid cultivation can be sustained once subsidies are removed.

Data on the most recent generation of hybrids released in the 2000s provide further insight into farmer acceptance of hybrid rice. Farmers' awareness of hybrid rice is higher in India's northern states (Uttaranchal (now Uttarakhand), Uttar Pradesh, Haryana, and Punjab) and central states (Chhattisgarh and Madhya Pradesh) than in the southern or eastern states—figures that correlate with regional adoption patterns (Figure 4.4). Surprisingly, among nonadopters, poor grain quality and lower market price for hybrid rice grain are not among the top five reasons for not growing hybrid rice. Rather, lack of awareness and high cost of seed are the top reasons (Figure 4.5). In these same northern states as above, the high cost of seed is the major reason for not adopting hybrid rice relative to the lack of awareness. However, in eastern states such as Jharkhand, West Bengal, and Bihar (as well as Karnataka and Tamil Nadu in the south), both high cost of seed and lack of awareness are major constraints. Overall, these data indicate that there are significant state and regional differences underlying farmers' rationale for adopting or not adopting hybrid rice.

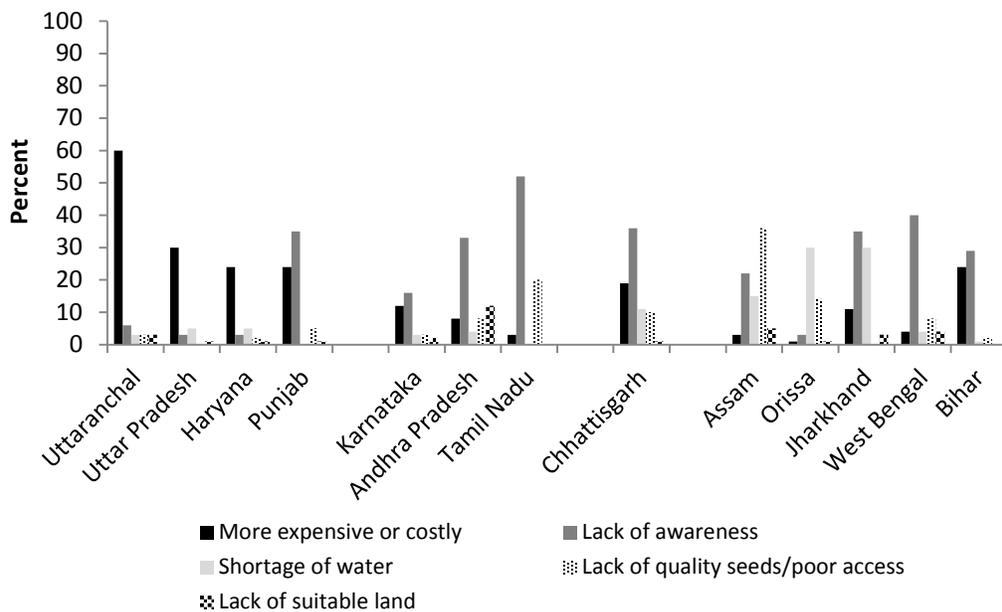
Figure 4.4—Awareness of and future likelihood of adoption of hybrid rice in India, 2008–09



Source: Francis Kanoi Marketing Research (2009).

Note: Although the state of Uttaranchal was renamed Uttarakhand in 2007, the state is denoted by its former name by Francis Kanoi Marketing Research (2009).

Figure 4.5—Top five reasons for not growing hybrid rice in India, 2008–09^{a,b}



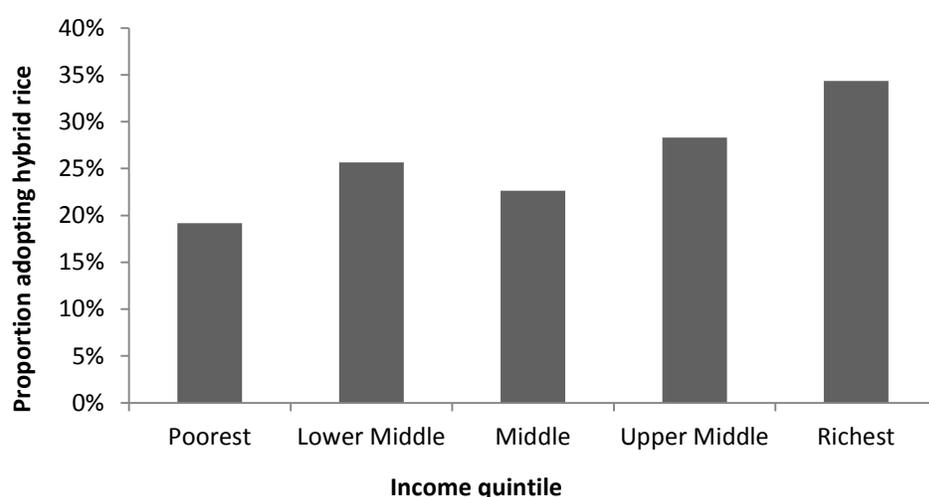
Source: Francis Kanoi Marketing Research (2009).

Notes: ^a Lack of information on hybrid seeds, no prior experience in hybrid seed cultivation, and no awareness about hybrid rice are combined together in the “Lack of awareness” category.

^b Although the state of Uttaranchal was renamed Uttarakhand in 2007, the state is denoted by its former name by Francis Kanoi Marketing Research (2009).

Data from the CSISA baseline survey (though limited to selected districts in Bihar, eastern Uttar Pradesh, Haryana, and Tamil Nadu, and thus not representative of India) suggest that most hybrid rice adopters in India tend to be relatively wealthy. Nearly 75 percent of all hybrid rice adopters have incomes above the poverty line, and more than half of all adopters have per capita incomes that fall in the upper-middle or upper income quintiles. In addition, as Figure 4.6 illustrates, the proportion of households adopting hybrid rice increases with increasing income. Although this correlation could simply reflect hybrid adoption increasing incomes, there are strong theoretical grounds for wealth or income conditioning the hybrid adoption decision. For example, greater income or wealth is often associated with larger landholdings, greater access to credit (which itself is often a function of an individual's landholdings), and lower absolute risk aversion, all of which are generally observed to facilitate earlier adoption of new (as compared with conventional) technologies such as hybrids (for example, Feder 1980).

Figure 4.6—Hybrid rice adoption in selected districts and states of India, by income quintiles, 2010



Source: Authors' creation based on data from CSISA (2011).

Table 4.4—Hybrid rice adoption in selected districts and states of India, by income quintiles, 2010

Income Quintile	Adoption Rate (%)
Poorest 20%	19.17 (–0.394)
Lower middle 20%	25.66* (–0.438)
Middle 20%	22.64 (–0.419)
Upper middle 20%	28.30** (–0.451)
Richest 20%	34.34** (–0.476)

Source: Authors' creation based on data from CSISA (2011).

Note: Standard deviations are provided in parentheses. Significance based on one-tail t-tests of group adoption rates among adjacent income groupings; * Significant at 5 percent level; ** Significant at 10 percent level.

An important aspect of the hybrid rice experience in India relates to the role of the private sector,⁸ and several trends are worth noting. First, current efforts by the private sector to promote hybrid rice are significant in eastern India, where yields for inbred varieties are already fairly low (~2.5 tons per hectare) and where the potential yield gains from cultivating hybrid rice may be more pronounced.

⁸ See Tripp and Pal (2001) for an early mention of the private sector's role in hybrid rice.

Second, private-sector efforts have also been significant in areas where the comparative advantage of hybrids—that is, higher yields—has offset the low prices of all rice in the market. This finding suggests that despite concerns about input costs, grain quality, and consumer acceptance, at least some farmers are finding it profitable to cultivate hybrid rice. Of course, the relative profitability of hybrid rice is determined not only by input costs and yield, but also by the signals determined by minimum support prices (MSPs) for rice in India, which was increased by 16 percent for the 2012–13 non-basmati rice crop. This coupled with a marked depreciation of the Indian rupee will change the calculus for hybrid rice farmers and rice farmers in general.

Third, the private sector is launching a new round of what it views as highly competitive hybrid rice lines for the market. Although the private sector accounts for only 20 of the 53 hybrid rice releases in India as of 2011 (Directorate of Rice Development 2011), private-sector products account for the majority of cultivated area under hybrid rice, as well as a significant portion of releases since 2008. Among these products are two particularly popular hybrids developed by the private sector: Arize 6444 from Bayer CropScience and PHB 71 from Pioneer Hi-Bred International, both of which were released more than 10 years ago.⁹ Several more recent releases have embodied the improvements in grain quality alluded to earlier.

These trends indicate strong potential for growth in India's hybrid rice market, perhaps especially among private-sector actors. The size of the seed market in 2008–09 was estimated at about 35,000 metric tons, with a total value of \$142 million (Francis Kanoi Marketing Research 2009). Although no complete estimates exist for the number of companies marketing hybrid rice seed, Kumar (2008) and Viraktamath and Nirmala (2008) estimated that there are between 30 and 60 companies engaged in developing hybrid rice varieties.

Still, the prolonged growth of the hybrid rice market will require further investment in development and delivery to boost its prevalence in farmers' fields. Several firms are investing heavily in R&D to improve yield performance, reduce yield variability, and improve grain quality. Spielman et al. (2011) estimated annual R&D investments by the private sector at \$9 million in 2009. In addition, many firms are also investing in the expansion of their marketing and distribution networks (Baig 2009; Francis Kanoi Marketing Research 2009; Viraktamath and Nirmala 2008). At present, there remains a dearth in private dealers providing farmers with access to hybrid seeds. In several states, most hybrid seeds that farmers acquire come from government suppliers, which provide only limited supplies to farmers at subsidized rates. Continued investment in private-sector R&D and delivery mechanisms has the potential to provide significant and sustained growth in the cultivation of hybrids in India.

The Bangladeshi Experience

In Bangladesh, the hybrid rice story is somewhat different from that in India. Although hybrid rice research began at the Bangladesh Rice Research Institute (BRRI) in 1993, it did not receive high priority on the public research agenda until after 2000. Rather, it was the private sector that took a lead in the introduction of hybrid rice, initially by importing seed from China to make up for shortfalls in domestic seed supply caused by floods in 1998–99 (Table 4.5). Subsequently, several companies expanded beyond bulk seed imports to the importation of parental lines from China from which to initiate their own seed production in Bangladesh. Several firms have also invested in adaptive research and product development for hybrid rice, as has BRAC, a large nongovernmental organization and currently a leader in the hybrid rice seed market.

⁹ Several experts interviewed for this study suggested that of the more than 100 hybrids in circulation in India, many are imitations and copycats of the popular commercial hybrids from Bayer CropScience and Pioneer Hi-Bred International mentioned earlier.

Already, some companies are claiming success in expanding the hybrid rice seed market in Bangladesh. Advanced Chemical Industries Ltd. (ACI), a leading agricultural concern in Bangladesh, released Allok-93024 in 2003, a hybrid that can potentially compete with BRRI Dhan 29, one of the most popular inbred rice varieties in Bangladesh (F. H. Ansarey, Md. Shafiqul Aktar, and Pabitra K. Bhanderi, ACI, pers. comm., 2012). Bayer’s latest hybrid releases are also reported to be (illicitly) making their way from India into the Bangladeshi market.

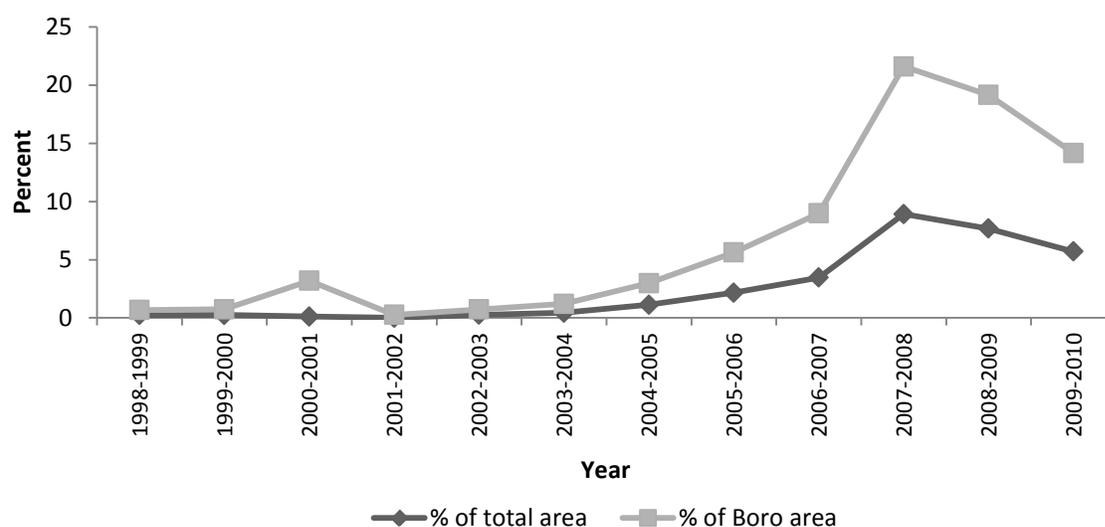
Table 4.5—Hybrid seed use and percentage share of imports in Bangladesh, 1998–2007

Year	Total Seed Used (metric tons)	Imported Seed as a Proportion of Total Seed Used (%)
1999	150	100
2000	227	88
2001	320	67
2002	556	63
2003	803	77
2004	1,472	73
2005	2,935	77
2006	6,524	71
2007	10,026	77

Source: Hossain (2008).

Despite the limited investment in research, hybrids represent a greater proportion of area under rice cultivation in Bangladesh than in India. Hybrid rice cultivation in Bangladesh peaked in the 2007-08 *boro* (winter) season—Bangladesh’s main rice-growing season—at 22 percent of total *boro* cultivated area, or 9 percent of all rice-cultivated area in the country (Figure 4.7). Hybrid rice cultivation has been mainly concentrated in Bangladesh’s northern districts, particularly within the Rajshahi and Rangpur divisions (Table 4.6). This is largely due to liberalization policies that have increased the proliferation of small-scale irrigation equipment for use during the dry *boro* season (Kürschner et al. 2010).

Figure 4.7—Hybrid rice cultivation, Bangladesh, 1998–2010



Source: Rashid, Julfikar, and Ali (2011), based on official figures.

Notably, Bangladesh has relied more on technology transfers in the form of hybrid rice seed and breeding lines from China than it has on own, in-country R&D (see Rashid, Ali, and Gisselquist 2012). This approach is significantly different from the one taken in India, where more concerted investments in public and private breeding have led to the homegrown development of rice hybrids for the Indian market. For countries such as Bangladesh, where public funding for research is limited and where few firms have the capacity to manage sufficiently large hybrid rice breeding programs, the importation of hybrid material seems to be an attractive strategy.¹⁰

Table 4.6—Hybrid rice adoption in Bangladesh, by division, 2011

Division	Hybrid Rice Adoption Rate (%)
Barisal	0.00
Chittagong	6.02
Dhaka	5.35
Khulna	9.74
Rajshahi	16.08
Rangpur	15.34
Sylhet	5.62

Source: Authors' creation based on data from IFPRI (2012).

Note: Figures represent the percentage of households cultivating land in each of the divisions that had cultivated hybrid rice from December 2010 through November 2011.

However, there is some inherent risk in the strategy followed in Bangladesh. First is the risk associated with the distribution of seed that may be poorly adapted to Bangladesh's agroecological context, crop management practices, farming systems, and consumer preferences.¹¹ This last aspect appears to be especially troublesome, because grain not suited for the tastes and preferences of consumers often results in a thin output market and lower prices. Given higher seed costs (compared with conventional inbred varieties), higher expenditures on complementary inputs, and lower output prices, margins between returns and costs become increasingly narrow. Although we do not have adequate data to state unequivocally that this mechanism has contributed to the decline in area under hybrid rice cultivation in Bangladesh, evidence consistent with this hypothesis does exist.

Consider Table 4.7, which reports farmers' perceptions about hybrid rice quality vis-à-vis conventional inbred varieties. Although a large share of the farmers perceive that the hybrids have better appearance and aroma than the conventional varieties, a relatively small share of farmers perceive that hybrid grain tastes better than the traditional varieties, that the stickiness of the hybrid grains after cooking is superior to that of traditional varieties, that the expansion of hybrid rice grain is superior to that of conventional varieties, or that the quality of hybrid grains can be maintained for an extended period. Although evidence may exist of improved perceptions for some of these categories, the improved perceptions still result in fewer than 40 percent of farmers deeming the hybrids as superior, at least as it pertains to some of these characteristics. Some of the hybrids recently released by the private sector were designed to address some of these quality issues to make hybrid grain more comparable to other conventional *boro* varieties, such as the widely cultivated BRRI Dhan 29.

¹⁰ A similar process may be unfolding in Pakistan, where Chinese seed has been imported and cultivated in recent years and where public and private research organizations have invested in adaptive research.

¹¹ As an example, in temperate Asia, such as Japan and China, sticky and soft rice is preferable. As such, *japonica* or *indica/japonica* hybrid varieties, which have generally low amylose content, are preferable, because these will result in grains that become soft and sticky during cooking (Kumar, Maruyama, and Moon 1994). In tropical South Asia, on the other hand, consumers prefer fluffier, nonsticky rice. Hybrids borne out of any combination with low-amylose *japonica* varieties (like those imported or derived from parental lines imported from China) will tend to result in grains that become soft and sticky during cooking, which consumers in those countries may perceive as being of lower quality.

Table 4.7—Farmers’ perceptions about quality of hybrid rice in Bangladesh

Quality/Characteristic	Farmers Reporting Same or Superior Quality/Characteristic as Compared with Inbred Rice (%)	
	2004	2005
Grain appearance	71	74
Taste of cooked rice	33	39
Stickiness of cooked rice	47	40
Aroma/Smell	82	77
Expansion after cooking	49	45
Quality of cooked rice after long hours ^a	20	34

Source: Azad, Mustafi, and Hossain (2008).

Note: ^a “Quality of cooked rice after long hours” relates to the taste and consistency of cooked rice when stored, cooled, and/or set aside after cooking.

The second risk results from the volatile and sometimes unpredictable nature of trade policy: should Chinese exporters or Bangladeshi importers be unable to (or choose not to) ensure a continuous flow of germplasm from year to year due to tariffs, regulations, or other barriers imposed by either trading partner, then the benefits of hybrid rice cultivation could dry up quickly. Although this is not a pressing concern for either country at the moment, China’s limited willingness to share its more advanced breeding lines and systems with other countries is an indication of just how significant trade barriers can be.

Studies from Bangladesh provide further insight into hybrid rice costs, returns, and adoption. In Bangladesh, hybrid rice is grown mainly during the dry (*boro*) season.¹² Even though annual yield variations have been recorded, hybrid yields are generally 15–30 percent higher than those of varieties (Azad, Mustafi, and Hossain 2008). Although farmers report some production cost reductions resulting from lower seeding rates and lower irrigation costs associated with early maturation, these savings are ultimately offset by higher fertilizer and pesticide use, further suggesting that the yield gains may be partly attributable to better management practices, in addition to the hybrid seed performance itself (Hossain 2008).

Azad, Mustafi, and Hossain (2008) also found that adoption rates were high among small farmers (less than 0.5 ha farm size) in 2004; in the subsequent year, however, adoption rates had increased among large farmers (greater than 2.0 ha farm size) and medium farmers (0.5–2.0 ha). Despite growing adoption, farmers initially faced lower market price for both grain (4–5 percent lower than varieties during the 2004 and 2005 seasons) and straw (9 percent lower than varieties in the 2007 season). Eventually, the grain price for hybrid rice did exceed the price for a competing inbred (BRRI Dhan 29)—by 4 percent in 2007—indicating that better hybrids, greater consumer/miller acceptance, or improved on-farm management practices may have entered the equation. Despite growing evidence of hybrid rice’s profitability in Bangladesh, the adoption rate of hybrids is still low, at 4 percent (Azad, Mustafi, and Hossain 2008). The benefits of higher yields, higher tillering ability, shorter maturity, and increased lodging resistance seem to be offset by the higher seed price, higher expenditures on other inputs (such as fertilizers and pesticides), poor cooking quality, and high pest and disease susceptibility in Bangladesh.

These analyses are limited insofar as they examine adoption from an ex post perspective. In addition, they provide limited characterization of adoption patterns disaggregated by socioeconomic characterizations. Azad, Mustafi, and Hossain (2008) surveyed farmers in 2004 and 2005 on their planned

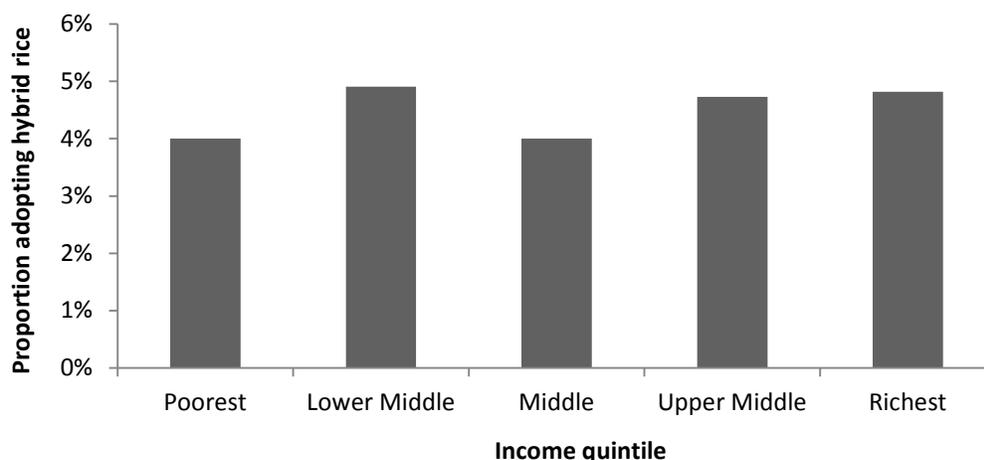
¹² This is somewhat a consequence of history. Hybrids were first introduced in Bangladesh during the 1999 *boro* season, after the government allowed the importation of 2,000 metric tons of hybrid seed following a 1998 flood that had destroyed a large volume of rice seeds (Azad, Mustafi, and Hossain 2008). Since then, most of the hybrids and other high-yielding varieties that have been distributed in Bangladesh have been *boro* varieties. In addition, the proliferation of shallow tubewells for irrigation has made it much more affordable to cultivate rice during this dry season, which has led to dramatic increases in the volume of land under rice cultivation during the *boro* season. Consequently, this also implies that enhancements to hybrid varieties to improve tolerance or resistance to most abiotic stresses will be of limited value to Bangladeshi farmers, because the most serious abiotic stresses (droughts, floods, or salinity) are of less consequence to irrigated farming systems during the dry *boro* season as compared with the rainy *aman* season.

use of hybrids in the following years (2005 and 2006) and disaggregated the responses by farm size, age, and education. Although their study finds no discernible pattern regarding adoption patterns based on farm size, it does find that younger and more educated farmers seemed more eager to cultivate hybrids.

Data from the more recent and nationally representative BIHS, on the other hand, suggest that farmers with larger landholdings are significantly more likely to adopt hybrid rice than farmers with either medium or small landholdings. Specifically, the BIHS suggests that poor households (those households with per capita incomes lower than \$1.25 per day, adjusted for inflation and differences in purchasing power) are less likely to adopt hybrid rice than nonpoor households. Rather ironically, it also suggests that households that have adopted hybrid rice do not, on average, have significantly higher incomes than those households that have not adopted. Unlike what was observed from the CSISA baseline household survey for Indian households, there does not appear to be any significant statistical relationship between higher income and a higher adoption rate for hybrid rice (Figure 4.8 and Table 4.8).

In Rajshahi and Rangpur divisions, however, where hybrid adoption rates are highest, some evidence exists that suggests household incomes are higher for hybrid rice adopters than for those households that have not adopted (though the income difference is only marginally significant in the Rajshahi sample). It should be noted that the Rangpur division has the lowest per capita income among all of Bangladesh’s divisions; thus, if hybrid rice cultivation does lead to higher incomes in Rangpur, increased hybrid rice adoption may prove a viable pathway for addressing poverty alleviation. For the country as a whole, however, fewer than 60 percent of hybrid rice adopters had incomes above the poverty line, compared with nearly 75 percent of hybrid rice adopters in the Indian sample drawn from the CSISA baseline survey.

Figure 4.8—Hybrid rice adoption in Bangladesh, by income quintiles, 2011



Source: Authors’ creation based on data from IFPRI (2012).

Table 4.8—Hybrid rice adoption in Bangladesh, by income quintiles, 2011

Income Quintile	Adoption Rate (%)
Poorest 20%	4.00 (0.196)
Lower middle 20%	4.91 (0.216)
Middle 20%	4.00 (0.196)
Upper middle 20%	4.73 (0.212)
Richest 20%	4.82 (0.214)

Source: Authors’ creation based on data from IFPRI (2012).

Note: Standard deviations are provided in parentheses. N statistical significance is found based on one-tail t-tests of group adoption rates among adjacent income groupings at the 1 percent, 5 percent, or 10 percent levels.

5. FUTURE SCENARIOS AND CHALLENGES FOR HYBRID RICE

Despite the technical and economic challenges posed by hybrid rice, interest in the technology remains significant in South Asia. Hybrid rice is high on the agenda of many public policymakers and corporate decisionmakers as a means of boosting stagnant yield growth, improving national food security, and raising incomes. Less cited, but of general interest to many, is the sustainable intensification of rice production on a smaller area of land to allow for greater diversification into other, higher-value crops. This section analyzes the key challenges associated with hybrid rice in South Asia by drawing on the conceptual framework described earlier. In particular, this section focuses on key constraints related to investment, collaboration, and risk management strategies associated with the stages of discovery, development, and delivery.

Scientific Discovery

The challenges facing hybrid rice in South Asia begin at the discovery stage, which is characterized primarily by the fundamental scientific and technical dimensions of the technology. These challenges represent broad classes of problems that are generally addressed over long time horizons and at a pre-commercial, preregulatory, and predistribution stage. We examine some of these constraints here. For further detail, see Xie and Hardy (2009).

First, researchers have been severely challenged in their efforts to secure high levels of heterosis in hybrid rice. China's impressive levels of heterosis have been developed for temperate-region rice hybrids, whereas much of South Asia requires tropical hybrids, in which heterosis is only 10–12 percent over the best inbred rice varieties. When adopting a new variety or hybrid, it is often the potential yield gain that farmers look for first; tropical rice hybrids are not yet providing a yield gain that is attractive enough to induce farmers to switch. An argument can easily be made that better management practices in the cultivation of inbred rice varieties—many of which also have attributes such as pest and disease resistance that are superior to the current generation of hybrids in South Asia—can generate comparable yield gains.

Second, researchers have been constrained by the limited effectiveness of the hybridization systems currently in use—in particular, the three-line male sterility system that is most commonly used in South Asia, but also the more advanced two-line system that is used in China. Further development of hybridization systems based on tools of genetic modification and (possibly) chemical hybridizing agents could accelerate hybrid rice research in the long run. In the short run, however, hybrid rice research will still depend on complex and sensitive systems of hybridization for rice.

Third—and of possibly less importance today than a decade ago—is the narrow germplasm base from which hybrid rice research is being conducted, which is in part a result of the limiting reliance on the male sterility system and in part a result of the absence of an effective heterotic genetic pool. This narrow base constrains the efficiency and output of hybrid rice breeding programs and, further down the line, creates high levels of pest and disease susceptibility in cultivated hybrid rice populations. Because of the lack of commercially usable cytoplasmic male sterile lines, development of hybrid rice outside China has been slower than expected (Virmani 1994), which poses difficulties for breeding hybrid rice with improved abiotic and biotic stress tolerance traits, better adaptation to different agroecological contexts, and better cooking and consumption qualities. Efforts to expand this narrow germplasm base are also hampered by China's implicit ban on the export or exchange of its most advanced materials for hybrid rice breeding, including female parental lines used in its superior two-line breeding system. That said, the narrow genetic diversity of female parents that plagued earlier generations of hybrid rice in South Asia is no longer viewed by researchers as the key issue, having been resolved by the creation of new female lines and new techniques for creating such lines.

Fourth, and related to this narrow germplasm base, has been the poor grain quality of hybrids, which initially led to low levels of consumer acceptance. This issue was of particular importance to farmers in high-productivity irrigated areas, who produce marketable surpluses, though possibly less so for farmers in rainfed or otherwise low-productivity areas, who produce for their own consumption. The key issue centered around amylose, the starch molecule that gives milled rice its specific appearance and character after cooking.¹³ Although there is significant variation in consumer preferences for rice across South Asia, higher amylose content (above 25 percent) is broadly reflective of generalized preferences in the region. In the past several years, researchers have been able to address this constraint, though cultivation of hybrid rice with these improved qualities is still reportedly at relatively low levels.

The general consensus from most scientists is that the available stock of scientific and technical knowledge is at a level at which many of these problems can be readily solved with sufficient time, effort, and resources. However, this also suggests that solutions will not be immediately available or remunerative in commercial markets. Thus, there is a need for both public and private investment in hybrid rice.

As with most crop research—including hybrid crops that are potentially lucrative in downstream markets—an optimal level of upstream public investment is required to translate the science into a viable technology. Public investment in R&D is generally more adept at solving basic problems constraining the effective use of a technology where longer time horizons and pre-commercial application are key characteristics. In addition, where neither private firms nor sovereign governments are willing to invest in removing these constraints—where the public good is global in nature—there is a case for international public investment in R&D efforts.

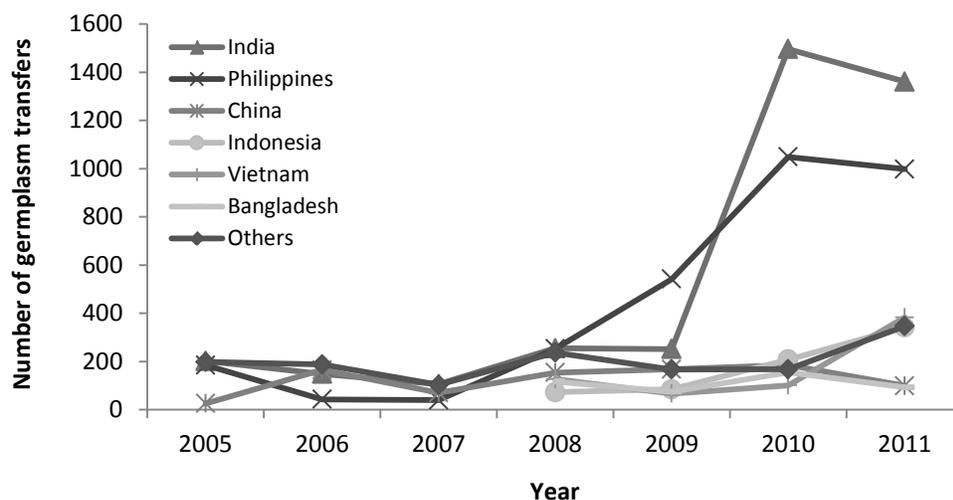
The international donor community, notably ADB and FAO, has financed hybrid rice R&D at IRRI, which began its research program on hybrid rice for tropical Asia in 1979. In 1988–89, IRRI released the two cytoplasmic male sterile lines, IR58025A and IR62829A, which are still used in most hybrid rice breeding programs in Asia today.¹⁴ Large-scale testing of hybrids developed from these lines followed in 1998, followed by the commercial release of hybrids in India (Sahyadri and CORH 2), Philippines (Mestizo), and Vietnam (HYT-57), among other countries.

In 2008, IRRI widened its commitment to hybrid rice research by establishing the Hybrid Rice Development Consortium (HRDC), a global platform designed to support research and share materials with public research agencies, private seed companies, and civil society organizations. Between 2005 and 2010, IRRI transferred more than 7,400 germplasm samples to other hybrid rice researchers around the world, with more than 70 percent of those transfers moving through the auspices of HRDC. Germplasm transfers have increased dramatically in recent years, with more than 80 percent of total transfers occurring from 2008 through 2010. Material transfers to India represent 33 percent of all transfers between 2005 and 2010 (Figure 4.9), though 61 percent of the total germplasm transfers to India occurred during 2010. Less than 5 percent of IRRI's total germplasm transfers have gone to Bangladesh, largely reflecting Bangladesh's heavy dependence upon material and seed transfers from China.

¹³ A higher amylose content (20–25 percent or more) gives cooked rice a high volume and dry quality with well-separated grains, whereas a lower amylose content (below 20–25 percent) gives cooked rice a moister, stickier quality (IRRI 2012a).

¹⁴ For example, IR58025A is the female parent for popular Indian hybrids such as PHB 71 marketed by Pioneer Hi-Bred International.

Figure 4.9—Germplasm transfers from IRRI’s hybrid rice research program, by country, 2005–2011



Source: Fangming Xie, 2012.

IRRI has further expanded its commitment to hybrid rice research under the Global Rice Science Partnership (GRiSP), with a planned investment estimated at \$15–17 million for South and Southeast Asia over five years; this figure does not include the related rice breeding work undertaken in other GRiSP components and IRRI programs that also support hybrid rice research or investments made by national partners.¹⁵ In addition, although national research organizations have made limited investments in hybrid rice to date (Table 4.9), they remain a necessary long-term complement to IRRI’s research.

Table 4.9—Research and development of hybrid rice in Asia, selected countries

Country	Research Initiated	First Hybrid Rice Released (number of releases)
India	1989	1994 (20)
Bangladesh	1996 ^a	1999 (4) ^b
Vietnam	1992 ^a	1992 (7)
Philippines	1993	1993 (3)

Sources: For research initiated: India: IRRI (2005); Bangladesh: IRRI (2005); Azad, Mustafi, and Hossain (2008); Vietnam and Philippines: Janaiah and Hossain (2003); for first hybrid rice released: India: DACNET (2007); Janaiah, Hossain, and Husain (2002); Bangladesh, Vietnam, and Philippines: Janaiah, Hossain, and Husain (2002); and Janaiah and Hossain (2003).

Note: ^a The first hybrids released in Bangladesh were imports from China and India; the first hybrids released in Vietnam were imports from China. See Janaiah, Hossain, and Husain (2002).

^b According to Azad, Mustafi, and Hossain (2008), hybrid rice research in Bangladesh was initiated in 1993 but only gained momentum in 1996.

¹⁵ GRiSP’s long-term goals aim at the adoption of new hybrid rice with at least a 15 percent yield advantage. Specific GRiSP milestones for hybrid rice are as follows: 50 new breeding populations developed and distributed to partners in South and Southeast Asia by 2011; 5,000 new hybrid parents and hybrids test-crossed and evaluated at IRRI and other locations in South and Southeast Asia by 2013; and 10 new hybrids released for commercial production by public- or private-sector partners in South and Southeast Asia in 2015. Budget estimates are for both Southeast and South Asia based on an assumption that hybrid rice is allocated an equal (17 percent) share of funding allocated to the six subthemes under Theme 2: “Accelerating the development, delivery, and adoption of improved rice varieties.” See IRRI/AfricaRice/CIAT (2010).

Arguably, hybrid rice research has suffered from donors' short-term outlooks and project funding cycles. Although some resources were allocated to public-sector research at both the national and international levels, there is a sense among many scientists that a large portion of the funding and scientific effort was allocated to capacity strengthening, demonstrations, and dissemination activities, all built around a limited set of hybrids and hybrid parent lines. In short, these funding commitments likely impeded early and rapid progress in addressing the technical challenges outlined above.

This then raises the question of the private sector's role in hybrid rice research. Private investment has been central to problem solving in the South Asian market, with multinational companies such as Bayer CropScience and Pioneer Hi-Bred International playing leading roles. Private-sector funding of research on these upstream issues is unlikely to fill the gap. In India, for example, private-sector spending on hybrid rice research is on the order of \$5–12 million per year. Additional estimates from key informants indicate private research spending on hybridization systems at \$1–2 million per year and on transgenic rice traits at \$3–5 million per year. On a global scale, however, these investments are just a small fraction of the private sector's overall R&D investment portfolio. By way of comparison, consider that current global investment for maize research is on the order of \$1.5 billion, and primarily from the private sector.

Despite the constraints imposed by insufficient investment and expenditure on hybrid rice research, the collaboration strategies being formed around hybrid rice are worth noting. IRRI's HRDC is a critical platform for collaboration between public research agencies and private seed companies on various aspects of hybrid rice research. IRRI's long-standing relationship with pivotal agencies in China's national agricultural research system is also a critical input to making expertise and materials available to consortium members and IRRI's partners. In addition, IRRI's forward-looking policies on intellectual property and public–private partnerships provide an avenue for supporting effective collaborations with firms that are willing and able to invest in hybrid rice. Although more rigorous evaluations of these various collaboration strategies are needed, there are strong indications of a relevant architecture for translating hybrid rice science from the public sector into viable hybrid rice technologies in the private sector.

The risks associated with hybrid rice research at the discovery stage pertain largely to the state of the science. One significant risk is associated with the use of tools derived from biotechnology—particularly genetic modification (GM)—in the development of improved hybridization systems. These hybridization systems are almost exclusively being developed in the private sector, with large multinational crop science firms taking the lead in their development. The associated risk relates to the nascent state of biosafety regimes in many Asian countries and the possibility that the use of GM-based hybridization systems cannot be effectively evaluated under current regulatory regimes. If this is the case, it is possible that biosafety regulators could revert to a *precautionary principle* that inhibits the introduction of hybrid rice derived from GM-based hybridization systems.¹⁶

A related risk comes from the long-term value of hybrid rice as a practical platform for launching GM traits in rice. Hybrid rice, like other hybrid crops, provides innovators with a biological form of IPR protection, because farmers have to purchase seed each season to realize the yield gains conferred by heterosis. Not only does this allow innovators to recoup their R&D investments in rice improvement, but it also creates an effective platform for continuous investment in developing GM rice traits, much like the experience in the hybrid and GM hybrid maize market in North America. Moreover, because firms can easily monitor their sales of hybrid rice seed, they gain a means of monitoring farmers' trait preferences, on-farm performance, and crop management practices, thus providing vital informational feedback mechanisms needed to support continued improvements and effective stewardship. However, the risks associated with the nascent or controversial biosafety regulations in some developing countries can limit the realization of this long-term value in hybrid rice.

¹⁶ For example, this precautionary principle was applied to Bt eggplant in India. Although Bt eggplant had reached the advanced stages of India's regulatory process in 2009, its release became the subject of an indefinite moratorium in 2010.

Technology Development

Solutions to the scientific and technical problems discussed earlier would encourage more serious investment by the private sector in hybrid rice product development. However, product development itself faces several key challenges that need to be addressed if hybrid rice is to generate welfare-improving and yield-enhancing impacts in South Asia.

A major difficulty facing hybrid rice is the production of high-quality hybrid seed. Technical requirements for hybrid seed production are sensitive, requiring careful management of breeding materials and the seed farms themselves. Unlike varietal rice, it is difficult to outsource hybrid rice seed production to smallholders, smallholder cooperatives, or community and village seed production schemes. The technical requirements for hybrid rice seed production represent a costly constraint on the production of marketable quantities of seed for all but the largest, most technically advanced, or well-capitalized seed companies in the market.

A second hurdle related to seed production is the protection of the intellectual property embodied in the seed. Private investment in seed-based technologies is partly determined by the existence of a credible IPR policy regime. Although hybrids provide the innovator—that is, the breeders, seed companies, and entrepreneurs—with a biological form of IPR protection, in turn providing them with a mechanism to recoup their investments in hybrid rice research, these biological IPR protections are more effective when backed by some form of legal protection. This is particularly valuable in situations where it is easy for competitors to steal parental lines from foundation seed and production fields, as is the case in both industrialized and developing countries. By ensuring that innovators have legal recourse allowing them to appropriate a portion of their innovation rents, plant variety protection (PVP) laws can incentivize private investment in hybrid rice development. In addition, through related requirements of disclosure, certification, and labeling, PVP laws can help address information asymmetries between farmers and seed retailers.

Unfortunately, few South Asian countries have sufficiently credible PVP laws. India's Protection of Plant Varieties and Farmers' Rights Act of 2001 provides the region's highest standard of protection. The large number of PVP applications submitted by the private sector for PVP certificates indicates that innovators take their legal protections seriously. However, the Indian courts' ability to adjudicate infringement cases in a timely manner remains to be demonstrated.

A number of other regulatory and risk management challenges need to be addressed to accelerate hybrid rice development in South Asia. These include streamlining of field testing procedures; improving seed certification, particularly the system of traceability from sole reliance on morphology to one that also incorporates the use of molecular markers; and (as noted earlier) strengthening the enforcement of PVPs so that spurious seed, copycats, and stolen breeding lines do not enter the market.¹⁷

Another regulatory issue emerges around the issue of competition and industry concentration. In most South Asian countries, the formal rice seed market is largely concentrated around the high-volume, low-margin varietal end of the business and is not what might be termed *cutting edge* in the seed industry. Only a few firms have entered the high-value, high-potential segment of the market with hybrid rice seed. With such a small number of companies in the hybrid seed market, there are concerns that large companies operating in highly oligopolistic conditions will be able to exert a high degree of market power over farmers—including small-scale, resource-poor farmers. This concern is often voiced in India—even though the hybrid rice market there is host to a fairly large number of companies (Spielman et al. 2011)—and in other countries where the market is much thinner. Continuous and careful analysis of market conditions, including competition and concentration, backed by effective enforcement of antitrust laws are necessary to ensure that seed markets remain competitive.

¹⁷ Several experts interviewed for this study suggested that of the more than 100 hybrids in circulation in India, many are imitations and copycats of the popular commercial hybrids from Bayer CropScience and Pioneer Hi-Bred International mentioned earlier.

The risk management issues of using hybrid rice as a platform for transgenic traits become more acute when considered at the product development stage. Risks are associated with individual traits conferred on hybrid rice (such as insect resistance or drought tolerance), stewardship of transgenic hybrid rice lines, gene flow issues to wild relatives, pollen flows to other rice varieties such as high-value basmati, and other such concerns. The biosafety policies and systems needed to assess and manage these risks are nascent in most South Asian countries and are the source of extensive public scrutiny and discourse. Given the recent experience with Bt eggplant in India, it is difficult to assume that the region's leader in GM crop development has a credibly functional regulatory regime that provides adequate risk assessment and management for transgenic crops. Although many experts interviewed for this study indicated that the Bt eggplant moratorium was not affecting private-sector decisions on investment in transgenic traits, it is unclear whether this will continue to be the case if the level of government capriciousness continues to be high. Creating a transparent regulatory environment to address these issues is therefore critical to the commercialization of hybrid rice containing potentially beneficial GM traits.

Product Delivery

Product delivery is possibly the weakest element in the hybrid rice innovation process. Despite its rapid and widespread adoption in China, hybrid rice has not caught on in a dramatic fashion in South Asia. Following the hybrid rice release in 1994 in the irrigated rice–rice and rice–wheat systems in southern and northern India, farmers in Andhra Pradesh, Tamil Nadu, and Karnataka complained of inconsistent yield performance, low grain quality, high susceptibility to pests, and other factors that led to significant levels of rejection and discontinued use (Janaiah 2002). Since then, hybrid rice has found its way to the more marginal agroecologies and markets of northeastern India, where the yield differentials against varieties in common use are more visible to smallholders.

Ultimately, the delivery and adoption of hybrid rice will depend on improvements made in the discovery and development stages. Although hybrid rice has immense potential for increasing productivity and improving overall welfare for the poor in many Asian countries, the challenges are not insignificant. Important challenges include increasing both seed and grain quality and customizing varieties to various agroecological conditions and consumer preferences. Addressing the challenges of grain quality and customizing hybrids to consumer preferences have important implications for the output prices that farmers receive for their grains. At present, the price penalty on hybrid rice at the farmgate places it at 10–20 percent less than coarse grain rice in both India and Bangladesh. Although breeders have made progress in increasing amylose content through conventional breeding efforts with better germplasm and molecular markers, the new hybrids coming on the market will need to overcome this price penalty to encourage adoption. The feedback mechanisms between the delivery stage and the discovery and development stages can facilitate these improvements. Further research is required to better understand the factors that motivate or constrain farmers' adoption of hybrid rice. Understanding these factors will help not only inform future discovery and development, but will also provide insight into potential policy responses that can speed up the widespread adoption of hybrids.

6. CONCLUSIONS AND POLICY RECOMMENDATIONS

This paper examines the processes and policies that encourage effective public and private investment in hybrid rice benefiting poor farmers in Asia, with an emphasis on India and Bangladesh. The paper identifies the roles of various organizations involved in advancing hybrid rice development and delivery and examines alternative incentives for enhancing the level and effectiveness of public and private investment in hybrid rice discovery, development, and delivery.

There is an immense stock of scientific knowledge and expertise on hybrid rice. Although much of this stock resides in China, high-quality expertise and accumulated experience also exists within the international agricultural research system, among multinational and domestic firms in the private sector, and in public research organizations in other Asian countries. More important, many of these actors are closely linked through a variety of scientific, professional, and product-related networks.

Several policy innovations could accelerate the discovery, development, and delivery of hybrid rice technology in Asia. First and foremost is the recommendation for further public investment in the upstream research on hybrid rice to develop the tools and technologies needed to advance hybrid rice. International and national funding for public research that addresses improved hybridization systems, grain quality, adaptation of hybrids to local agroecological conditions, and germplasm diversity can provide the platform for more applied plant breeding to develop improved hybrids by both the public and private sectors.

Second is the need to improve the innovation incentives that may ultimately encourage more private investment in hybrid rice development—that is, the policies and institutions needed to encourage investment in hybrid rice by public research organizations, private firms, and farmers themselves. Stronger IPR policies and enforcement could encourage the entry of complementary private investment, while other policy incentives could accelerate the dissemination and commercialization of public research on hybrid rice that is sitting on the shelf or otherwise confined to academic use.

At the same time, more creative approaches to funding hybrid rice research are needed to provide long-term and sustained private funding for hybrid rice research. One example is a unique foundation-based funding experiment in India. The Barwale Foundation (formerly the Mahyco Research Foundation) is a nonprofit organization that promotes research, technology, and knowledge in the areas of agriculture, healthcare, and education for human welfare (Barwale Foundation 2009). The foundation's investment in hybrid rice research—one of the organization's five in-house research projects—illustrates how private-sector research can be geared toward supporting more applied research and product development. Barwale's research agenda includes a number of activities essential to hybrid rice breeding, such as identification of fertility restorer lines and cytoplasmic male sterility sources, molecular tagging and mapping, and the multiplication and distribution of IRRI germplasm.

At the delivery/adoption end of the spectrum, careful thought needs to be given to the use of public resources to subsidize hybrid rice seed and complementary inputs. Although subsidies have strong historical precedence in encouraging the adoption of new technologies in South Asia, such interventions may ultimately work against widespread adoption and the growth of a competitive hybrid rice seed industry. South Asia's experience with input subsidies suggests that price distortions can lead to rent-seeking behavior and elite capture among certain types of farmers and industries, thus impeding market growth and efficiency in the long run.

Another set of policy recommendations relates to the future of hybrid rice as a platform for pro-poor GM crop development in Asia. Cotton in India provides an interesting comparison to rice in Asia. The introduction of cotton hybrids and a GM insect-resistance trait (Bt) occurred almost concurrently, resulting in a large-scale transformation of the Indian cotton sector. Although rice is primarily a food crop for own consumption and for sale to the market among smallholders in South Asia, and although cotton is primarily a fiber crop for sale in well-defined markets, similar technological trajectories might be drawn in years to come. However, this outcome depends acutely on the design and implementation of credible regulatory regimes to manage the risks associated with biotechnology and GM crops.

In summary, hybrid rice has the potential to change the face of rice cultivation in Asia. The basic outcome of stable, better adapted, and commercially accessible hybrid rice could translate into a range of positive impacts: enhanced rice productivity; increased on-farm incomes for smallholders; and reductions in the land required for intensive rice production, which in turn allows for reallocation to other agricultural and nonagricultural activities. However, the innovation process is far from complete. Significant scientific, technical, and policy challenges exist at each stage—discovery, development, and delivery—and repeated iterations of research and development need to be pursued. The ability of public policymakers, corporate decisionmakers, scientists, entrepreneurs, and farmers to understand these challenges and anticipate solutions is fundamental to the long-term success of hybrid rice in Asia.

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