Public Expenditures, Private Incentives, and Farmer 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 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.

Key words: Hybrid rice, agricultural research and development, technological change, innovation, South Asia

JEL codes: Q16, Q18, O31, O33

1. INTRODUCTION

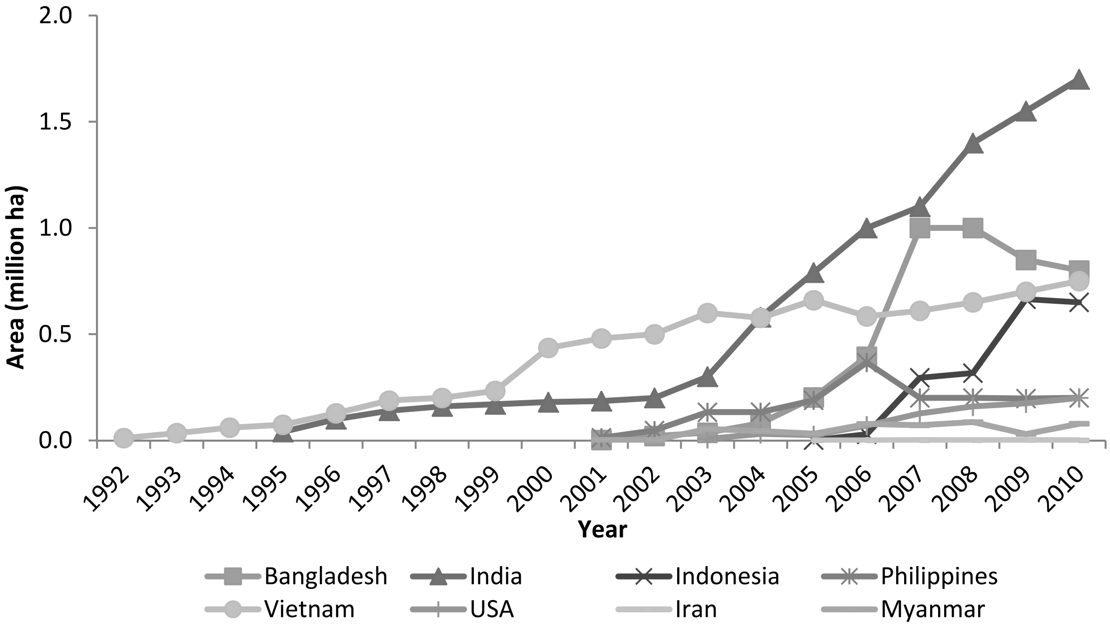
Hybrid rice cultivation represented an estimated 63 percent of all area under rice cultivation in China in 2009, and has contributed significantly to increasing national rice yields and output (Li, Xin, and Yuan 2009). The contributions have, in turn, contributed to improving food security by feeding an estimated 60 million additional people per year in China.

Beyond China, numerous studies suggest that hybrid rice can positively contribute to food security in Asia by increasing food staple availability for own-consumption by farm households, 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. Moreover, because hybridization provides innovators with the ability to recoup their investments in research, hybrid rice represents a technology platform on which both public and private sector scientists can contribute to continuous improvement. As such, many policymakers in Asia see hybrid rice as a means of closing the gap between rice supply and demand, 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 only slightly more than 10 percent in Vietnam (Figure 1). Hybrid rice adoption is moving slowly in Asia. A range of technical challenges, market failures, and policy constraints have limited the diffusion of hybrid rice outside of China to date.

One way of analyzing this issue is to examine the processes behind the product—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. To this end, this paper examines hybrid rice development by focusing on the processes through which new technologies are transformed into economically relevant products. It does so with the application of novel analytical approach to agricultural science, technology, and innovation.

Figure 1. Hybrid rice cultivation, selected countries excluding China, 1992–2010



[a] Source: Doberman, International Rice Research Center, pers. comm., 2011

This framework helps identify (a) the key actors, assets, and processes engaged in the production, exchange, and use of new technologies; (b) the actions and interactions that enable these actors to invest in process innovations; and (c) 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 where policy interventions are most likely to result in accelerated development and delivery.

This paper proceeds as follows. Section 2 provides background on hybridization and hybrid rice. Section 3 discusses the analytical approach used here to better understand science, technology, and innovation policy. This is followed by a description of data and data sources used in this paper in Section 4. Section 5 discusses the "product discovery" stage of hybrid rice's life cycle and the technical challenges it still faces. Section 6 discusses the "product development" stage of the life cycle, including market opportunities, regulatory hurdles, and other constraints. Section 7 discusses the "product delivery" stage, with an emphasis on science policy, industry structure, and key institutional issues. Section 7 concludes with a set of actionable policy recommendations for further research, development, and delivery of hybrid rice, with particular reference to India and Bangladesh.

2. BACKGROUND

The discovery of "hybrid vigor" dates back to work conducted by Charles Darwin in the 19th century (see Birchler, Yao, and Chudalayandi 2006). 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, Cold Spring Harbor, NY. Schull later proposed the term "heterosis" to describe hybrid vigor. In the mid 1910s, experiments with maize hybrids conducted by Donald F. Jones at the Connecticut Agricultural Experiment Station, New Haven, CT 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 stagnant maize yields in the U.S. (Fernandez-Cornejo 2004; USDA 1962).

Importantly, the release of this first hybrid also led to the emergence of a commercial seed industry in the U.S. Because the yields gains conferred by heterosis decline dramatically after the first (F1) generation of seed, farmers must purchase new F1 seed each season to continually capture these yield gains. This characteristic, along with continuous public and private investment in upstream maize research, contributed to the development of a lucrative seed industry during the 1930s which saw the entry of many small and medium size seed companies breeding and marketing hybrid maize seed to farmers.

As a result, almost all maize cultivated in the US was grown from hybrid seed beginning in the 1960s. Annually, maize receives over US$1 billion in private research and development investment in the US (Fernandez-Cornejo 2004; Fuglie et al. 1996), more than any other crop, owing largely to its market value and the incentives that hybridization provides to private breeders.

Beyond the U.S., hybrid maize cultivation has spread throughout the world, including developing countries in Latin America, and Sub-Saharan Africa and Asia (Morris 1998). Hybrids of other crops such as sorghum, pearl millet, and cotton, have also made similar inroads in developing countries (Pray and Nagarajan 2010).

Yet despite the lucrative benefits of hybrids to both firms and farmers, there are substantial criticisms and concerns with respect to their place in developing-country agriculture. First and foremost is the concern that purchased hybrid seed is too costly for many resource-poor, small-scale farmers in developing countries (Kuyek 2000). However, evidence suggests that purchased seed, both OPV and hybrid, is far more common than conventional wisdom suggests. This is true even in South Asia, where poverty rates among small-scale farmers are highest in Asia (Table 1), even with respect to rice, a crop that is commonly associated with seed saving.

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. While there is compelling evidence to suggest that some seed markets are highly concentrated in some countries, and that corporate pricing strategies maybe be welfare-reducing for farmers in certain instances, the question of market power is essentially an empirical one, requiring careful and context-specific analysis.

Third is the concern that hybridization leads to greater risk in the form of (a) lower in situ genetic diversity and greater susceptibility to pests and disease, and (b) fewer management alternatives to cope with weather-related production risks, particularly for resource-poor, small-scale farmers who have limited access to credit, insurance, and other services that help manage risk. The extent to which these factors are significant concerns depends again on context and situation.

In short, despite criticisms of commercially marketed hybrid seeds for smallholders, the welfare tradeoff 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.

Table 1. Seed replacement rates in India, 2007

Crop	Seed replacement rate (%)
Wheat	25.23
Rice	25.87
Maize	44.24*
Sorghum	19.87*
Millet	48.47*
Soybean	33.39
Sunflower	62.88*
Cotton	15.3*

Source: Seednet (2007)

Note: *Includes seed replacement rates for both open pollinated varieties and hybrids

Rice hybridization

There is much diversity in how farmers, scientists, and consumers have responded to hybrid rice in Asia, with varying consequences for food security and agricultural productivity. We examine the emergence of hybrid rice here.

The possibility of rice hybridization was first documented in 1954 by S. Sampath and H.K. Mohanty at the Central Rice Research Institute, Cuttack in the Indian state of Orissa (Janaiah 2002). But concerted research and development efforts actually began a decade later in China (Li, Xin, and Yuan 2009).

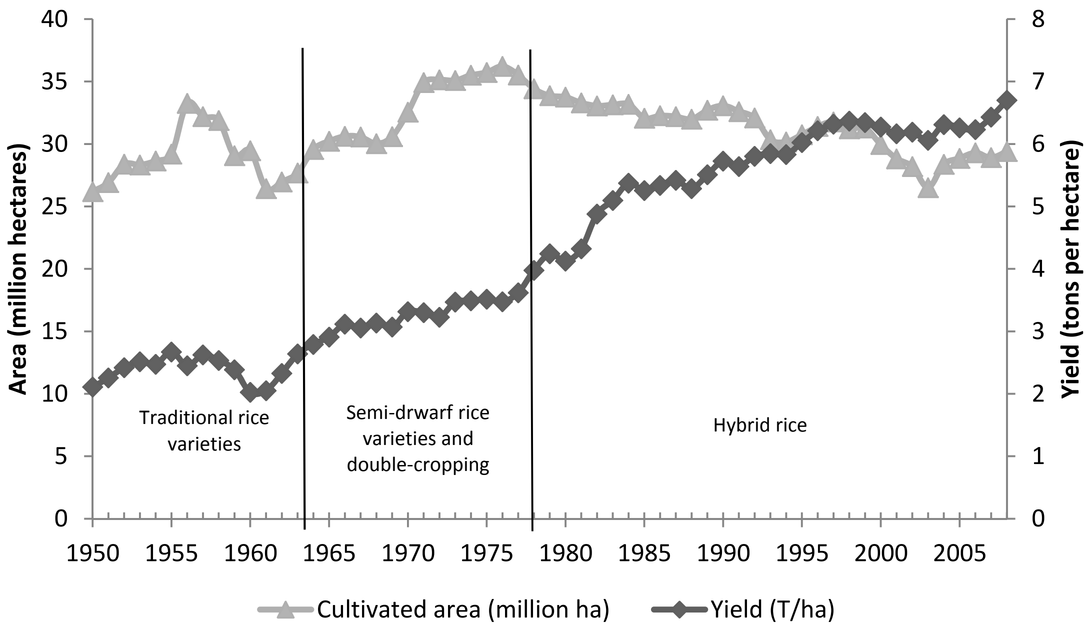
China's substantial investments in hybrid rice were focused on the significant technical challenges associated with hybridization: finding sterile lines that could be crossed with fertile lines to generate the stable expression of heterosis in an otherwise self-pollinating crop.[1] By the mid 1970s, 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 out-yield traditional

[1] While cross-pollination or outcrossing does occur in cultivated rice, it occurs at very low levels averaging at around 5percent. See Virmani (1994).

and semi-dwarf rice varieties while also providing adequate levels of stress tolerance, responsiveness to inputs, and grain quality that is increasingly acceptable to consumers.

Hybrid rice now accounts for 63 percent 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 has contributed to a 67.5 percent increase in national rice yields, raising average yields from 3.4 to 6.7 tons per hectare during this period (Figure 1). 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).

Figure 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 Center.

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 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), several studies find high returns owing to a combination of higher yields and lower labor and non-labor 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. In short, China's success in promoting hybrid rice is the result of a long-term investment program that engaged both the public and private sectors with farmers.

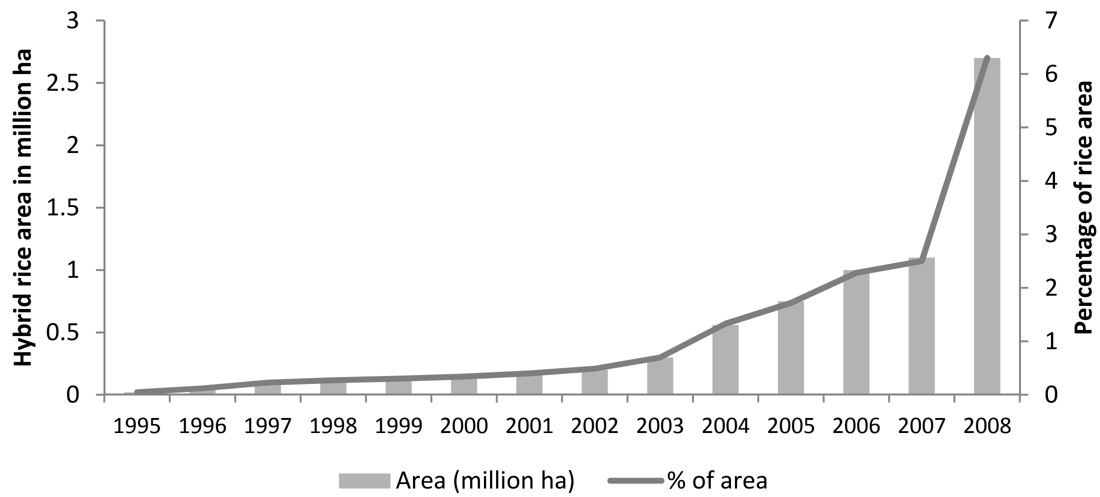
Hybrid rice development in other Asian countries has followed a different path. In India, for example, systematic research on hybrid rice began only in late 1989 under a relatively small program under the Indian Council on Agricultural Research (ICAR) (Janaiah 2002). Since then, the development and delivery of hybrid rice in India has faced several significant challenges that may delay the government's goal of introducing hybrid rice on 25 percent of all cultivated rice area by 2015. Narrow germplasm availability resulting from technical constraints on the number of female lines converted in the male sterility system resulted in grain quality issues and poor levels of abiotic and biotic stress tolerance (Janaiah 2002; Janaiah and Hossain 2003). Poor grain quality of hybrids released in the early 1990s resulted in low levels of acceptance by Indian consumers. A weak male sterility system has also limited the number of female and restorer lines resulting in a narrow germplasm base and in problems with production of quality hybrid seed.

Forty-two rice hybrids have been released for commercial cultivation in India (Baig 2009; see Annex). This includes 28 hybrids from the public sector and 14 from the private sector, including two particularly popular hybrids (Arize 6444 from Bayer and PHB 71 from Pioneer Hi-Bred International, both of which are more than 10 years old). In addition to these officially released hybrids, many more truthfully labeled private hybrids are also available in the market, suggesting that more than 100 rice hybrids are currently in circulation in India (Kumar 2008).

The size of the Indian hybrid rice market during 2008–2009 was estimated at about 35,000 metric tons with a total value of $142 million (Francis Kanoi 2009). Although there are no complete estimates for the number of companies marketing hybrid rice seed, Kumar (2008) and Viraktamath and Nirmala (2008) put the figure at between 30 and 60. Several of these firms are investing heavily in R&D to improve yield performance, reduce yield variability, and improve grain quality. Many other firms are investing in the expansion of their marketing and distribution networks (Baig 2009; Francis Kanoi 2009; Viraktamath and Nirmala 2008).

Since 2005, the proportion of area under hybrid rice has grown at a rate of about 40 percent per year, albeit from a low base (Figure 3). This has occurred most markedly in six northern and eastern states of India where rice yields are low relative to the national average. In those states, private hybrids account for more than 95 percent of area under hybrid rice cultivation (Baig 2009; Francis Kanoi 2009; Viraktamath and Nirmala 2008).

Figure 3. Area under hybrid rice cultivation in India, 1995–2008



Source: Authors' calculations based on Baig (2009) and Francis Kanoi (2009).

In Bangladesh, on the other hand, hybrid rice seed was largely imported directly from China (Table 2) at the outset of the technology's introduction. Key experts interviewed for this study indicate that only a few companies are engaged in multiplying hybrid rice seed from Chinese breeding lines in Bangladesh, and only the Bangladesh Rice Research Institute, a few companies, and BRAC (a non-governmental organization) are involved in adaptive research and product development.[2] These levels of activity suggest a fairly limited level of research, which means that there is insufficient breeding work being conducted on hybrid rice in Bangladesh to render it more suitable to local agroecological conditions, crop management practices, or consumption preferences, or to ensure competitiveness against imports of poorly adapted Chinese hybrid rice seed. The risks of introducing poorly adapted hybrids are high. 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.

Table 2. 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: Vien and Nga (2008) for Vietnam and Hossain (2008) for Bangladesh

[2] Interestingly, experts interviewed for this study also reported that BRAC was multiplying hybrid rice seed for export to Indonesia.

For countries such as Bangladesh and Pakistan, where public funding for research is limited and where there are few firms with the capacity to manage sufficiently large hybrid rice breeding programs, the importation of hybrid seed is an attractive strategy. However, there is some level of risk not only from the use of poorly adapted hybrid seed, but also from the volatility of trade policy: should Chinese exporters or domestic importers be unable to (or choose not to) ensure a continuous flow of seed from year to year due to tariffs, regulations, or other barriers imposed by either trading partner, the benefits of hybrid rice cultivation could dry up quickly. While seed from the next generation (F2) of a hybrid will grow and can be saved by farmers, the yields they would receive from this F2 generation would be reduced.

In short, there is a lot of interest in hybrid rice in South Asia among public policymakers and corporate decisionmakers, despite the many challenges ranging from the adaptive research stage and continuing through to on-farm adoption and consumption. We analyze these challenges in greater detail below.

3. CONCEPTUAL FRAMEWORK

Before doing this, however, we provide a conceptual framework to guide the analysis. There are obvious challenges in transforming a technology such as hybrid rice into an economically relevant production factor input to agricultural production. The persistence of these challenges suggests that a better understanding is needed of how the factors of production—scientific capital, technical know-how, breeding materials, and seed production systems—are being translated into real outputs such as marketable quantities of hybrid rice seed.

One way of developing a better understanding of these issues is to examine the policies and processes that translate science into viable technologies and, ultimately, into commercial products. This means shifting our analytical emphasis to the question of how, rather than why, science, technology, and innovation (ST&I) policies and investments should be made.

Moreover, this calls for an approach to ST&I policy research that extends beyond the "black box" approach to measuring inputs and outputs, and instead conducts more in-depth analysis of the underlying ST&I processes in developing-country agriculture to identify how specific knowledge gaps can be bridged.

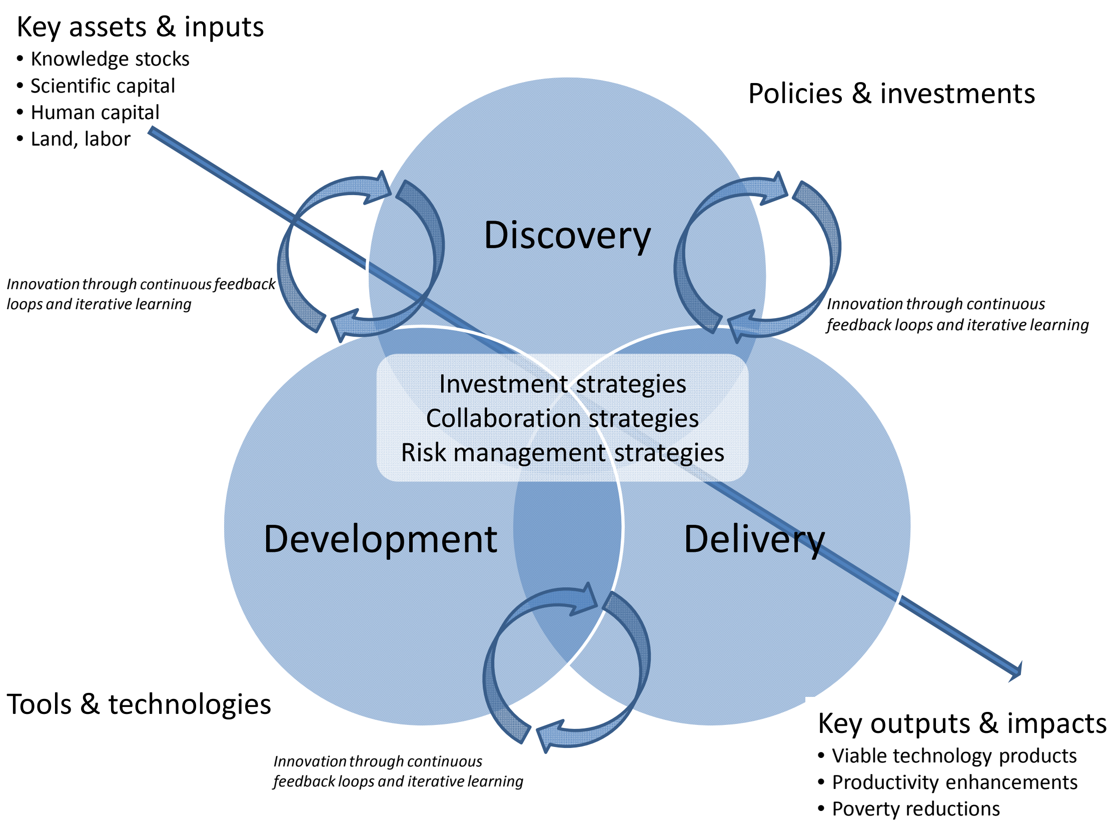
The ST&I framework used here answers the how question by emphasizing the study of the roles played by diverse actors in the production, exchange, and use of ST&I products and processes; the institutions that condition these actors' actions and interactions; and the precise policy interventions that are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

The basis of this framework is three stages of analysis—discovery, development, and delivery. Figure 4 illustrates this conceptual framework. In essence, the figure highlights the overlaps across discovery, development, and delivery, drawing attention to the fact that few technological opportunities can be exploited simply on the basis of a linear process that moves upstream science into downstream applications. Each stage is further broken down into three focal topics: investment strategies, collaboration strategies, and risk management strategies.

Figure 4 illustrates a process that translates ST&I into welfare-improving impacts. 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; and 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 non-linear 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, while ST&I can contribute to solving problems in developing-country agriculture, the solutions require more than just good science. They require the right tools and technologies *plus* the right policies and investments.

Figure 4. From discovery to delivery: The ST&I framework



Source: Authors

Table 3 provides another perspective on the ST&I framework by identifying the specific types of issues that that emerge in each of these stages and areas. At each stage, there are clearly defined investment, collaboration, and risk management strategies that innovators and policymakers must address by making critical decisions and pursuing specific actions. Where information and analysis are limited, and where public policies give little guidance to 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 far-sighted public policies is an essential contribution of any analytical work on ST&I.

Table 3. 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 and/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 IPR needs to identify licensing or collaboration priorities	Identify and leverage product development networks and partnerships	Manage in-house vs. 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

4. 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. Key sources are as follows.

Key informant interviews: Information was gathered from a series of unstructured interviews held in 2008–2010 in several locations across India.[3] Interviews were conducted with a range of

[3] Key informant interviews were conducted with financial support from the IFPRI Strategic Innovation Fund and the Cereal Systems Initiative for South Asia (CSISA).

persons knowledgeable about the seed and agbiotech industries in India, 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 5 provides a breakdown of key informants by sector. Questions covered during the interviews were related to seed and agbiotech market opportunities in India (with specific reference to rice, wheat, and maize), R&D investment strategies and constraints, product delivery strategies and constraints, IPRs, technology forecasts and opportunities, and regulatory issues.

Table 4. Key informants interviewed, 2008–2010

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

Source: Authors.

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: 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 main objectives of the study 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 (those with more than 30,000 hectares under rice cultivation) in the 16 major rice-growing states in India for the 2008–2009 agricultural season.

Secondary data sources. Data are extracted from a range of sources including peer-reviewed journal articles, government statistical reports, private databases, and documents from industry sources. In addition, data were extracted from a commissioned study on hybrid rice in Bangladesh by Ar-Rashid et al. (2011).

5. DISCOVERY, DEVELOPMENT, AND DELIVERY OF HYBRID RICE

The following section examines hybrid rice from the perspective of the conceptual framework set forth above. Each section identifies the key constraints related to investment, collaboration, and/or risk management strategies associated with the stages of discovery, development, and delivery.

Discovery: The technical constraints to advancing hybrid rice

The challenges facing hybrid rice in Asia begin at the discovery stage, where the fundamental scientific and technical dimensions of hybrid rice research remain constraining factors. First is the limited effectiveness of the hybridization systems currently in use, particularly the two- and three-line male sterility system that is in common use. 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.

Second is the narrow germplasm base from which hybrid rice research is being conducted, itself partly a result of the limiting reliance on the male sterility system in place and partly because 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).

The next challenges relate more to upstream science that must be addressed to develop viable technologies and marketable products. First is the issue of poor grain quality and high amylase content that limits hybrid rice's desirability to millers and consumers. Second is the lack of sufficient adaptation to local agroecological conditions in South Asia, including both biotic and abiotic stress tolerance.

Experts interviewed for this study agree that the stock of scientific and technical knowledge on hybrid rice and hybridization systems is at a level at which many of these problems could be solved with appropriate research investment. There are no miracle breakthroughs required to improve hybrid rice performance. In fact, similar problems have been solved to develop hybrids in other crops in other countries, while some of these specific problems have been solved for hybrid rice in China.

So why are these challenges viewed as issues at the "discovery" stage? The answer relates partly to the nature of these challenges—broad classes of problems affecting hybrid rice that are generally addressed on longer time horizons and at a pre-commercial, pre-regulatory, and pre-distribution stage. Activities undertaken at the discovery stage are rarely remunerative in commercial markets, and often produce knowledge and information that are public (non-excludable and non-rival) good in nature. As such, investments made at the discovery stage often generate social returns that exceed private returns, resulting in market failures that result in the chronic undersupply of new knowledge and information. Such market failures frequently necessitate public investment in ST&I.

As with most crop research—including hybrid crops that are potentially lucrative in downstream markets— there is an optimal level of upstream public investment 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.

Public and private investment. Where neither private firms nor sovereign governments place value on investments that yield potentially high social returns, the market failure is the result of what is commonly termed as a "global public good." Agricultural research often fits this description, and is thus the recipient of bilateral and multilateral funding to support the international network of international agricultural research centers under the Consultative Group on International Agricultural Research (CGIAR).

The International Rice Research Institute (IRRI), one of the earliest CGIAR centers, is the key actor when it comes to the production of rice-related R&D that is characteristically a global public good. IRRI began its research program on hybrid rice for tropical Asia in 1979, and in 1998−89 released the two cytoplasmic male sterile lines, IR58025A and IR62829A, that are still used in most hybrid rice breeding programs in Asia today.[4] 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. And in 2008, IRRI established the Hybrid Rice Development Consortium to further promote this work through a regional platform of public research agencies, private seed companies, and civil society organizations.

Despite more than 30 years of work on hybrid rice at IRRI, its expenditure on hybrid rice has been fairly modest when viewed as a portion of its overall portfolio. Funding from the Asian Development Bank and several other donors have been critical to sustaining the hybrid rice program at IRRI, but arguably, the funding has not been sufficient to address the scientific and technical challenges at the discovery stage.[5]

Arguably, hybrid rice research at IRRI has also suffered from donors' short-term outlooks and project funding cycles. While significant resources were allocated to research and research personnel in IRRI projects such as those funded by the ADB, there is a sense that a large portion of the funding and scientific effort were allocated to capacity strengthening, demonstrations, and dissemination activities, all built around a limited set of hybrids and hybrid parent lines. Given the stage of hybrid rice development outside of China, it would seem that more, and more sustained, investment in the development of hybridization systems and viable parent lines would have been a higher priority.

National research organizations in countries such as India, Indonesia, Philippines, Thailand, Vietnam and Malaysia are also key actors in discovery-stage activities on hybrid rice (Table 5), and a critical, long-term complement to IRRI's research on global public goods. Hybrid rice research has been ongoing in these countries since the late 1980s and early 1990s, with funding provided from IRRI, ADB, the Food and Agriculture Organization of the United Nations (FAO), and national budgets. In India, the main sources of funding have been provided under projects of the Indian Council for Agricultural Research (1989-2003), UNIDO and FAO (1991-96 & 1999-2001), Mahyco Foundation (1997-2000), IRRI's ADB project (1999-2000), and the National Agricultural Technology Project (funded by the World Bank) and Ministry of Agriculture (2003-2008).

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

[5] By way of comparison, consider that current global investment for wheat research is on the order of $250 million, and for maize research on the order of $1.5 billion.

Table 5. **Research and development of hybrid rice in Asia, selected countries**

Country	Research initiated[a]	First hybrid rice released[b]
India	1989	1994
Bangladesh	1996[c]	1999
Vietnam	1992	1992
Philippines	1993	1993/1994

[a] India: IRRI (2005); Bangladesh: IRRI (2005), Azad, Mustafi and Hossain (2008); Vietnam, Philippines: Janaiah and Hossain (2003)
[b] India: DACNET (2007); Bangladesh, Vietnam, Philippines: Janaiah and Hossain (2003)
[c] According to Azad, Mustafi and Hossain (2008), hybrid rice research in Bangladesh was initiated in 1993 and gained momentum in 1996.

Unfortunately, national funding to hybrid rice research has been limited, not unlike international funding. Moreover, national agricultural research systems are largely dependent on donor funding which has proven to be fairly short-term and volatile in past decades. In short, these funding levels are likely insufficient to addressing the technical challenges outlined above.

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, with estimates from key informants interviewed for this study ranging from $5 million to $30 million. 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. Yet these expenditure figures and research priorities do not represent complete solutions to the five technical challenges identified earlier.

Collaboration and partnership. Despite the constraints imposed by insufficient investment and expenditure on hybrid rice research, the collaboration strategies being formed around hybrid rice are quite notable. IRRI's Hybrid Rice Development Consortium is a critical platform for collaboration between both 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. And IRRI's forward-looking policies on intellectual property and public-private partnership provide a clear and effective focus on ensuring that effective collaborations with firms that are willing and able to invest in hybrid rice. While more rigorous evaluations of these various collaboration strategies are needed, there are strong indications that there exists a relevant architecture for translating hybrid rice science from the public sector into viable hybrid rice technologies in the private sector.

Risks and risk management. The risks associated with hybrid rice research at the discovery stage pertain largely to the state of the science. First and foremost is the pest and disease susceptibility associated with a dependence on a narrow germplasm base and the low in-field genetic diversity of hybrid rice.

Of equal importance is the risk 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 cropscience firms taking 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 not unlikely that biosafety regulators would revert to a "precautionary principle" that inhibits the introduction of hybrid rice derived from GM-based hybridization systems.[6]

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 since 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, since 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 information 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.

Product development: The regulatory challenges for hybrid rice

Solutions to the scientific and technical problems outlined 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.

The first hurdle discussed below is the design and enforcement of a credible intellectual property rights (IPR) policy regime that sufficiently encourages private investment in product development and marketing. The second hurdle relates to regulatory issues that will influence the rate at which hybrid rice is commercialized and released. The third hurdle relates to the risk management issues alluded to earlier, which become more urgent when viable technology products are developed on a hybrid rice platform.

Intellectual property rights. Because hybrid seed cannot be grown beyond the F1 generation without a significant loss of yield, farmers buy, rather than save, seed each season. This characteristic provides innovators—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 R&D.

Nonetheless, biological IPRs are more effective when backed by some form of legal IPRs, especially in a situation where it is easy for competitors to steal inbred parent lines from foundation seed and production fields, as is the case in many 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. And through related requirements of disclosure,

[6] For example, this precautionary principle was applied with respect 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.

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 (PPV&FR 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.

India also provides the region with an example of an alternative mechanism to encourage private investment in R&D— the proposed "Protection and Utilization of Publicly Funded Intellectual Property Bill, 2008," or "Innovation Bill." Loosely derived from the United States' Bayh-Dole Act of 1980, the Innovation Bill would allow public researchers, research organizations, and universities to patent their research, license their research for commercial use, and secure remuneration in exchange for commercial use (Unnikrishnan 2010; DST 2008). Although the exact provisions of the proposed legislation have not received the full attention of India's policymakers in recent sessions, the Innovation Bill could contribute to the rapid development and commercialization of hybrid rice in India, with potential spillover effects in neighboring countries such as Bangladesh.

Seed production issues. The difficulty in producing hybrid seed in sufficient quantities and quality poses a challenge for product development due to the relatively sensitive conditions required for seed multiplication. Hybrid rice seed production is a difficult task requiring careful management of breeding materials and the seed farms themselves. And unlike with varieties, it is difficult to outsource 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 production of marketable quantities of seed for all but the largest, most technically advanced, or well capitalized seed companies in the market.

Regulatory issues. There are a number of fundamental regulatory and risk management challenges that need to be addressed to accelerate hybrid rice development in South Asia. This includes streamlining of field testing procedures, improving the system of traceability from sole reliance on morphology to one that also incorporates the use of molecular markers; and (as noted above) strengthening the enforcement of PVPs so that spurious seed, copycats, and stolen breeding lines do not enter the market. Several experts interviewed for this study suggest 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. And in Bangladesh, the hybrids in circulation are largely Chinese hybrids that were released over a decade ago and have, in many cases, been replaced in China with better performing next-generation hybrids.

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 farmers—including small-scale, resource-poor farmers—will be compelled to purchase expensive seed from large companies operating in highly oligopostic markets. This is a concern in India, where the hybrid rice market is host to a fairly large number of companies (Table 6, Figure 5), and in other countries where the market is much thinner (Table 7).

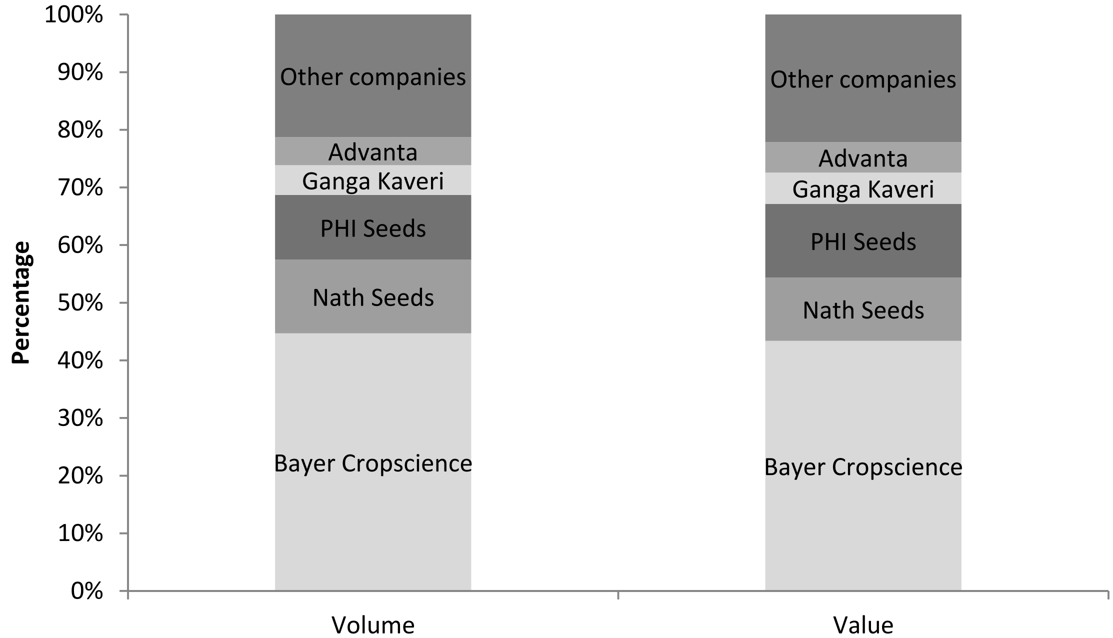
There are also concerns that the relatively small financial importance of South Asian seed markets may make it relatively attractive for large companies to initiate and terminate marketing efforts based on internal considerations of profit and loss, and not on the urgent productivity and poverty impacts of their technologies. Without effective enforcement of anti-trust laws and without market growth and development, these issues are likely to attract much scrutiny from policymakers, media, and civil society. See Spielman et al. (2011) for further insights into this issue.

Table 6. Characteristics of the Indian rice seed market, 2008–2009

Indicator	Inbred varieties	Hybrids	
		Public	Private
Percentage of farmers using	93.7	0.2	6.1
Percentage of area under	93.8	0.3	5.9
Seed rate (kilograms/hectare)	56.0	11.0	13.0
Seeds used ('000 metric tons)	2,321.8	1.4	33.7
Quantity of seeds purchased ('000 metric tons)	1,174.5	1.4	33.7
Market value (US$ millions)	489.0	3.7	131.5
Yield (metric ton/hectare)	4.3	6.6	5.2

Source: Francis Kanoi (2009).

Figure 5. Structure of India's hybrid rice seed market by volume and value, 2008–2009



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

Table 7. Seed companies in the development and delivery of hybrid rice, selected Asian countries, 2004

Country	Private companies	NGOs	Public seed enterprises	Total
Bangladesh	4	1	1	6
Indonesia	6	-	2	8
India	20	2	7	29
Myanmar	4	-	-	4
Philippines	4	-	-	4
Sri Lanka	3	-	-	3
Thailand	1	-	-	1
Vietnam	5	-	4	9

Source: IRRI 2005

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 (e.g., insect resistance or drought tolerance), stewardship of transgenic hybrid rice lines, geneflow 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, as discussed earlier, nascent in most South Asian countries and the source of extensive public scrutiny and discourse. Given the recent experience with Bt brinjal 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. While many experts interviewed for this study indicated that the Bt brinjal 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. Thus, creating a transparent regulatory environment to address these issues is critical to the commercialization of hybrid rice containing potentially beneficial GM traits.

Product delivery: The market and adoption issues facing hybrid rice

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 its 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 disadoption (Janaiah 2002).[7] 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.

A review of the cost and return data on hybrid rice provide some insight into hybrid rice performance and the variability in performance. As shown in Table 8, there is a high degree of variability in performance between countries.

The most extensive work on the costs, returns, and determinants of hybrid rice adoption has been carried out in India. For example, an analysis of farm-level data conducted by Janaiah (2002) in five major rice growing states (Andhra Pradesh, Karnataka, Tamil Nadu, Orissa, and West Bengal) during the 1997-98 crop year concluded that newly released hybrids were not profitable for rice farmers in India. Overall, the analysis found that while hybrids demonstrated yield gains in Andhra Pradesh and Karnataka, because of the high susceptibility to pests and diseases, their yields were lower in Orissa and Tamil Nadu.

In an effort to overcome these problems, a new set of hybrids targeting irrigated production systems of south and north India were introduced during late 1990s along with a 50 percent seed subsidy to rice growers. Despite the breeding improvements and seed subsidy, studies by Chengappa, Janaiah and Gowda (2003), Janaiah (2003), and Ramasamy et al. (2003) of hybrid rice grown in the 2000-01 crop year reported mixed outcomes. Many initial adopters of hybrid rice in states such as Andhra Pradesh, Tamil Nadu and Karnataka dropped out of hybrid rice production, while hybrid yields beat inbreds only in Andhra Pradesh and Karnataka, and not in Tamil Nadu.

The studies by Chengappa, Janaiah and Gowda (2003), Janaiah (2003), and Ramasamy et al. (2003) also reported 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

[7] The slow adoption of hybrid rice in India stands in contrast to the experience in China, where approximately 65 percent of rice area under is hybrid. This has been explained in a number of ways including the larger research investment of the Chinese government, the ability of the Chinese government to support and require adoption of hybrids, and the overall better quality and yield of Chinese rice hybrids (Li, Xin, and Yuan 2010).

quality and poor rice head recovery during milling meant that the net returns to hybrid rice were frequently lower than varieties. Ultimately, farmers abandoning hybrid rice cited a long list of reasons for their disadoption including poor grain quality, low market price, high seed cost, non-availability of quality seeds, susceptibility to pests and diseases, low head-rice recovery, and chaffy or sterile grains.

Table 8. 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*	279*	29.0
2005	8.2	6.6	24.2	547	524	4.4	604*	412*	47.0
2007[a]	7.3	6.0	22.0	717	727	-1.5	431*	197*	119
2007[b]	7.3	5.4	35.0	717	696	3.0	431*	194*	123
Vietnam									
2004 WS	5.4	5.3	2	583	541	8	na	na	na
2004 DS	6.3	5.8	10	565	564	0	na	na	na
2006 Summer	5.4	5.2	4	Na	na	na	+15[b]		
2007 Spring	6.4	6.2	3	Na	na	na	+28[b]		
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
2008-09[c]	5.2	4.3	21.0	402	340	18	673	590	14.0
2008-09[c,d]	5.2	4.3	21.0	402	340	18	565	590	-4.0

Source: Azad, Mustafi and Hossain (2008) and Hossain (2008) for Bangladesh; Pandey and Bhandari (2008), and Vien and Nga (2008) for Vietnam; Sebastian and Bordey (2005) and David (2006) for Philippines; Janaiah and Hossain (2003) and authors' calculation based on Kanoi (2009) for India.
Note: Net return calculation includes straw value for Bangladesh.
[a] Against inbred BR 29.
[b] Against inbred BR 28.
[c] Authors' calculations, comparing net returns to hybrid rice against overall returns to rice production from Francis Kanoi (2009), assuming no market price differential for hybrid rice grain. See Annex.
[d] Assuming a market price discount of 10 percent for hybrid rice grain.

Data from Francis Kanoi (2009) provides further insight into farmer acceptance of hybrid rice. Farmers' awareness of hybrid rice is higher in India's northern and western states than those in the south or east—figures that correlate with regional adoption patterns. Surprisingly, among adopters, 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 expensive seed or higher costs of cultivation are the top reasons (see Annex).

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. Even though annual yield variations have been recorded, hybrid yields are generally 26 percent higher than those of varieties (Table 8). While 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).

A study by Azad, Mustafi and Hossain (2008) found that adoption rates were high among small farmers (<0.5 ha farm size) in 2004, but in the subsequent year, adoption rates had increased among large farmers (>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 (BR 29)—by 4 percent in 2007—indicating that better hybrids, greater consumer/miller acceptance, and/or improved on-farm management practices may have entered the equation. Despite growing evidence of hybrid rice's profitability in Bangladesh, 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, poor cooking quality, and high pest and disease susceptibility in Bangladesh.

These studies are limited in so far as they examine adoption from an ex post perspective. Further study of the ex ante benefits of hybrid rice are needed. Also needed is a better understanding of the risks associated with hybrid rice as a platform for GM trait delivery. Hybrid rice containing GM traits requires that additional attention be paid to risk management—bioafety evaluations, monitoring of refugia management, and safe product stewardship. As noted above, the current capacity in many Asian countries to design, manage, and enforce credible biosafety regulations is limited. This raises issues related to environmental, economic and social risks in hybrid rice's future.

Ultimately, the delivery and adoption of hybrid rice will depend on improvements made in the discovery and development stages. While hybrid rice has immense potential for increasing productivity in many Asian countries, and for improving smallholder welfare, the challenges are not insignificant.

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 for the poor, 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. While much of this stock is resident in China, there are also high-quality expertise and accumulated experience within the international agricultural research system, among multinational and domestic firms in the private sector, and in public research organizations in other Asian countries. Importantly, many of these actors are closely linked through a variety of scientific, professional, and product-related networks.

There are several policy innovations that 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—developing 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—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 incentives such as India's proposed Innovation Bill could encourage more 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 public 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 non-profit organization that promotes research, technology and knowledge in the areas of agriculture, health care and education for human welfare (Barwale Foundation 2009). The foundation's investment in hybrid rice research—one of their five in-house research projects—illustrates how public sector research can be geared toward supporting more applied research and product development. Their 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.

Another set of policy recommendations relate 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 genetically modified insect resistance trait (Bt) occurred almost concurrently, and resulted in a large-scale transformation of the Indian cotton sector. Although rice is primarily a food crop for own consumption and sale to the market among smallholders in South Asia, and while cotton is primarily a fiber crop for sale in well-defined markets, a 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 that allows for reallocation to other agricultural and non-agricultural activities. However, the innovation process is far from complete. There are significant scientific, technical, and policy challenges at each stage—discovery, development, and delivery—and repeated iterations of research and development that 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 hybrid rice's long-term success in Asia.

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References

Alston, J. M., G. W. Norton, and P. G. Pardey. 1998. *Science under Scarcity: Principles and Practice for Agricultural Research Evaluation and Priority Setting*. The Hague: CABI.

Ar-Rashid, H., A.W. Julfiquar, and S. Ali. 2011. History, impact and current status of hybrid rice research, development and delivery in Bangladesh. Dhaka: Agricultural Advisory Society.

Azad, M.A.S., B.A.A. Mustafi, and M. Hossain. 2008. Hybrid rice: Economic assessment of a promising technology for sustainable food grain production in Bangladesh. AARES 52nd Annual conference, Rydges Lakeside, Canberra, Australia.

Baig, S. U. 2009. Hybrid Rice Seed Scenario in India: Problems and Challenges. Available online at http://www.apsaseed.org/docs/00b9aab6/ASC2009/SIG/HybridRice/Rice_India.pdf. Accessed June 2010.

Barwale Foundation 2009. *Barwale Foundation Annual Report 2008-09.* Hyderabad, AP: Barwale Foundation.

Birchler, J.A. H. Yao, and S. Chudalayandi. 2006. Unraveling the genetic basis of hybrid vigor. *Proceedings of the National Academies of Science* 103: 12957–12958.

Chengappa, P.G., A. Janaiah, M.V. S. Gowda. 2003. Profitability of hybrid rice cultivation: Evidence from Karnataka. Economic and Political Weekly 38 (25): 2531-2534.

DACNET.2007. Available online at http://dacnet.nic.in/rice/Rice%20Varieties%20in%20India.htm. Accessed June 2010.

David, C. 2006. The Philippine hybrid rice program: A case for redesign and scaling down. Research Paper 2006-03. Makati City, Philippines: Philippine Institute for Development Studies (PIDS).

DST (Department of Science and Technology, Government of India). 2008. Innovation bill, 2008. <http://www.dst.gov.in/draftinnovationlaw.pdf>. Accessed June 2, 2010.

Fernandez-Cornejo, J. 2004. *The seed industry in U.S. agriculture: An exploration of data and information on crop seed markets, regulation, industry structure, and research and development*. Agriculture Information Bulletin AIB 786. Washington, D.C.: U.S. Department of Agriculture Economic Research Service.

Fuglie, K., N. Ballenger, K. Day, C. Klotz, M. Ollinger, J. Reilly, U. Vasavada, and J. Yee. 1996. *Agricultural research and development: Public and private investments under alternative markets and institutions.* Agricultural Economics Report 735. Washington, D.C.: U.S. Department of Agriculture Economic Research Service.

He, G. T., and J. C. Flinn. 1989. Economic efficiency of hybrid and conventional rice production in Jiangsu Province, China. In *Progress in irrigated rice research*. Selected papers and abstracts from the International Rice Research Conference, September 21–25, 1987, Hangzhou, China. Manila, Philippines: International Rice Research Institute.

He, G. T., X. G. Zhu, H. Z. Gu, and J. S. Zhang. 1988. The use of hybrid rice technology: an economic evaluation. In *Hybrid Rice*: Proceedings of the International Symposium on Hybrid Rice, October 6–10, 1986, Changsha, Hunan, China. Manila, Philippines: International Rice Research Institute.

Hossain, M. 2008. Performance and potential of hybrid rice production in Bangladesh. Paper presented at the International workshop on hybrid rice held in Changsa, China, 12-15 September 2008.

IRRI (International Rice Research Institute).2005. Terminal report of the IRRI-ADB project: Sustaining food security in Asia through the development of hybrid rice technology. Los Banos, Philippines.

Janaiah A, M. Hossain 2003. Can hybrid rice technology help pro-ductivity growth in Asian tropics? Farmers' experiences. Econ.Political Weekly 38(25):2492-2501.

Janaiah, A. 2002. Hybrid rice for Indian farmers: Myths and realities. *Economic and Political Weekly* 37 (42): 4319–4328.

Janaiah, A. 2003. Hybrid rice in Andhra Pradesh: Findings of a survey, Economic and Political Weekly, 38(25): 2513-2516.

Janaiah, A. and M. Hossain. 2003. Can hybrid rice technology help productivity growth in Asian Tropics? Farmers' Experiences, Economic and Political Weekly, 38(25): 2492-2501.

Kabir, H. and H. Arrashid. 2004. Prospects and potentials of rice hybrids in Bangladesh: A special study. Dhaka: Agricultural Advisory Society.

Kanoi, F. 2009. A study on paddy in India: 2009. A syndicated report on seeds. Francis Kanoi Marketing Research, Chennai, India.

Kumar, I. 2008. Hybrid rice an Indian perspective. Available online at http://apsaseed.org/images/lovelypics/Documents/SCs/Hybrid%20rice_india.pdf. Accessed June 2010.

Kuyek, D. 2000. Hybrid rice in Asia: An unfolding threat. Mimeo.

Li, J., Y. Xin, and L. Yuan. 2009. *Hybrid rice technology development: Ensuring China's food security.* IFPRI discussion paper no. 00918. Washington, D.C.: IFPRI.

Lin, J. Y.1991. The household responsibility system reform and adoption of hybrid rice in China', *Journal of Development Economics* 36: 353-72.

Lin, J. Y. and P. L. Pingali. 1994. An economic assessment of the potential for hybrid rice in Tropical Asia: Lessons from Chinese experience' in S. S. Virmani, (ed) *Hybrid Rice Technology – New Developments and Future Prospects,* Manila, the Philippines, IRRI.

Morris, M.L. 1998. *Maize Seed Industries in Developing Countries.* Boulder, Colo.: Lynne Rienner.

Pandey, S., and H. Bhandari. 2008. Economics of hybrid rice: Issues and opportunities. Unpublished presentation. Los Baños, Philippines: International Rice Research Institute (IRRI).

Pelegrina, W.R., P.P.I. Borja, M.G.M.P. Hilario, S. Jallorina, and J.L. Yasol. 2008. Hybrid rice and the mirage of rice self sufficiency. *SEARICE Review* (Nov): 1–16.

Pray, C.E., and L. Nagarajan. 2010. Pearl millet and sorghum improvement in India. In *Proven Successes in Agricultural Development: A Technical Compendium to Millions Fed,* D.J. Spielman and R. Pandya-Lorch, eds. Washington, DC: IFPRI.

Ramasamy,C. A. Janaiah, A., K.N. Selvarajan, and M. Hossain 2003. Hybrid rice in Tamil Nadu: Evaluation of Farmers' Experiences, Economic and Political Weekly, 38(25): 2509-2512.

Rao, P. 2009. Indian seed industry status and future: Field crops. *NSAI Magazine* (Jan-Mar): 7–11.Smale, M. and T.S. Jayne. 2010. "Seeds of success" in retrospect: Hybrid maize in Eastern and Southern Africa. In *Successes in African Agriculture*, S. Haggblade and P. Hazell, eds., pp. 71–112. Washington, D.C.: Johns Hopkins University Press/International Food Policy Research Institute.

Sampath, S and H.K. Mohanty. 1954. Cytology of semi-sterile rice hybrid. *Current Science* 23: 182-83.

Sebastian, L.S. and F.H. Bordey. 2005. Embracing hybrid rice: Impacts and future directions. Paper presented at the SEARCA seminar series. University of the Philippines, Laguna. July 19, 2005.

Seednet. 2007. *Seed replacement rates, 2007.* <http://seednet.gov.in/Material/SRR-08.pdf>, accessed May 2, 2010.

Spielman, D.J., D. Kolady, A. Cavalieri, and N.C. Rao. 2011 (forthcoming). The Seed and Agricultural Biotechnology Industries in India: An Analysis of Industry Structure, Competition, and Policy Options. IFPRI discussion paper. Washington, DC: IFPRI.

Tao, S. K. 1987. Evaluation of the economic benefit of single-cropping hybrid rice in comparison with inbred rice. *Hybrid Rice* 1: 10–11.

Unnikrishnan, C. H. 2010. House panel suggests drastic changes to innovation bill. <http://www.livemint.com/2010/06/07001522/House-panel-suggests-drastic-c.html>. Accessed June 15, 2010.

USDA (United States Department of Agriculture). 1962. *Yearbook of Agriculture.* Washington, D.C.: USDA.

Vien, T.D., N.T. D. Nga. 2008. Economic impact of hybrid rice in Vietnam: An Initial assessment. Available online at http://www.grain.org/research_files/Vietnam.pdf. Last accessed July 2012.

Viraktamath, B.C. and B. Nirmala. 2008. Economics of hybrid rice seed production in India. Available online at http://hrdc.irri.org/images/5thHybridRiceSymposiumPresentations/47.%20Nirmala_Economics%20of%20HR%20Seed%20Production%20in%20India.pdf/. Accessed June 2010.

Virmani, S. S. 1994. Hybrid rice technology: new developments and future prospects. Selected papers from the International Rice Research Conference. International Rice Research Institute, Manila, Philippines.

Virmani, S.S. 1998. Advances in the development and use of hybrid rice technology for increasing global rice production. Paper presented at the First National Workshop for Strengthening National Capacity for Hybrid Rice Development and Use, Munoz, Philippines, August 5–6.

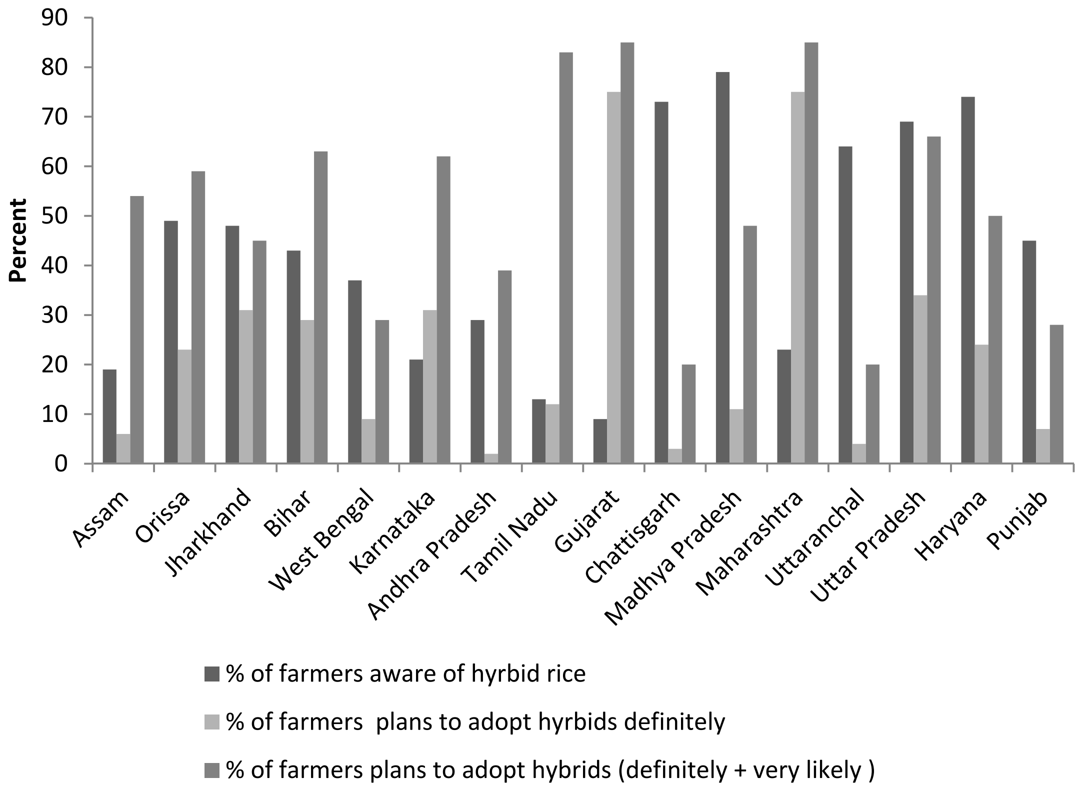
ANNEX

Calculating the costs and returns to hybrid rice cultivation

The calculation of costs and returns to hybrid rice cultivation based on data from Francis Kanoi (2009) was conducted as follows. Kanoi (2009) provides hybrid- and inbred-specific data on yields and seed prices, but not on other inputs. Instead Kanoi (2009) provides costs and returns data for overall rice production in India. We conducted a partial budget analysis under the assumption that inbred production costs are similar to these overall production costs, plus the additional cost of seeds (available from the Francis Kanoi (2009) data, plus an assumed 15 percent additional cost for fertilizer, pesticides, weedicides, irrigation, harvesting and transportation. Similalry, since Francis Kanoi (2009) does not provide hybrid- and inbred-specific data on market price, net returns are calculated under two scenarios: first, assuming no price discount; second, assuming 10 percent price discount. The value of by-products (straw) is not included in these net return calculations.

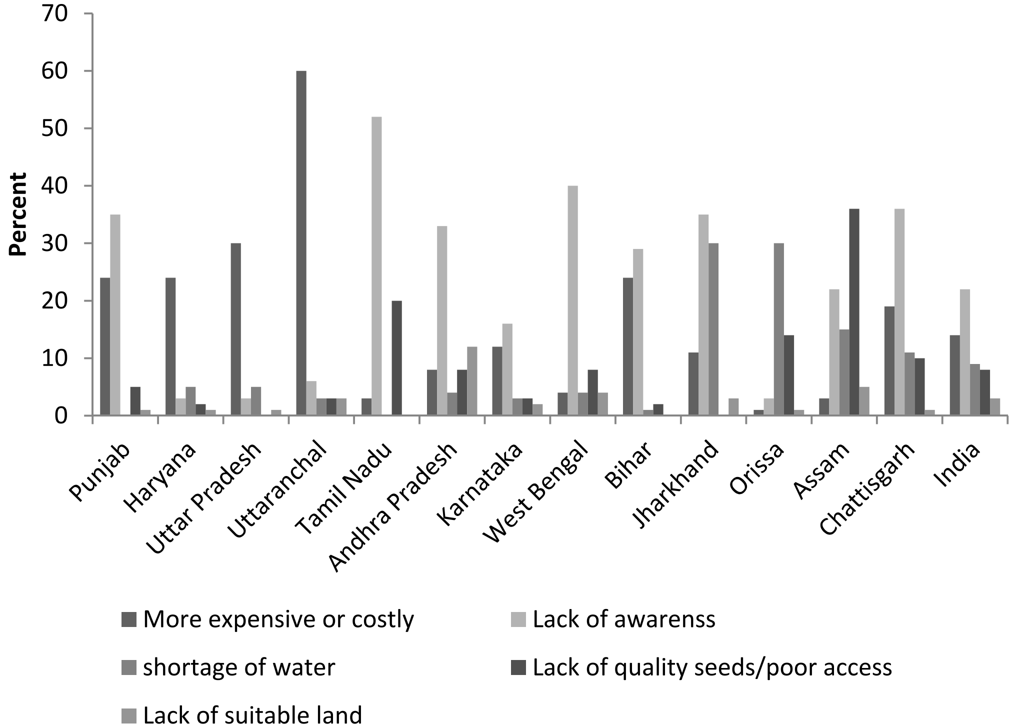
ANNEX: Farmers' perception of hybrid rice

Awarenss of and future likelihood of adotpion of hybrid rice 2008-2009 India



Source: Kanoi (2009)

Top five reasons for not growing hybrid rice 2008-09, India



Source: Authors' calculation based on Kanoi (2009)

Note: Lack of information on hybrid seeds, no prior experience in hybrid seed cultivation, and no awareness about hybrid rice are combined together in the category lack of awareness.

In northern states such as Haryana, Uttar Pradesh and Uttaranchal high cost of cultivation is the major reason for not adopting hybrid rice. However, in eastern states (West Bengal, Bihar, Jharkhand) and Chhattisgarh (West) lack of awareness is the major constraint. Overall, this analysis indicates that there are state and regional-wise differences in the reasons for not adopting hybrid rice.