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Intellectual Property Rights, Private Investment in Research, and Productivity Growth in Indian Agriculture

A Review of Evidence and Options

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ABSTRACT

With the growth of private investment in developing-country agriculture, new advances in the biological sciences, and rapid integration of developing countries into the global trading system, intellectual property rights (IPRs) have become an important concern for policymakers, corporate decisionmakers, and many other players in the agricultural sector. But there are still unanswered questions about whether emerging and evolving IPR regimes in developing countries will contribute to increasing agricultural productivity and improving food security. This paper attempts to answer some of these questions by tracing the effects of IPRs on private investment in crop genetic improvement and, in turn, on agricultural productivity. The paper focuses specifically on the case of India, the regional leader in implementing IPRs in agriculture. Findings indicate that maize and pearl millet yields grew significantly during the last two decades due to the combination of (1) public policies that encouraged private investment in India's seed industry during the 1980s, (2) public investment in hybrid breeding programs that generated new materials offering substantial yield gains, and (3) biological IPRs conferred by hybridization that conveniently married the private sector's need for appropriability with the nation's need for productivity growth. Although past lessons are not an indication of future success, this convergence of policy solutions and technology opportunities can be replicated for other crops that are vital to India's food security.

Key words: intellectual property rights, agricultural research and development, agricultural productivity, food security, India

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1. INTRODUCTION

With the growth of private investment in developing-country agriculture, new advances in the biological sciences, and rapid integration of developing countries into the global trading system, intellectual property rights (IPRs) have become an important concern for policymakers, corporate decision makers, and many other players in the agricultural sector. Yet IPRs are a relatively new policy intervention in many developing countries and are still the subject of debate.

IPRs are a means of promoting innovation by granting innovators with temporary access to market power over a technology product so that they may accumulate profits and recoup their investment in research and development (R&D), and they are an established part of many modern economies. In the agricultural sector, there is sufficient evidence to suggest that IPRs have influenced private investment in R&D as intended, particularly with respect to crop genetic improvement.

But few studies have extended their inquiries to determine whether IPRs, by encouraging private R&D investment, have actually increased agricultural productivity. The few studies that do exist have found fairly mixed results for both industrialized and developing countries.

This raises the question of whether emerging and evolving IPR regimes in developing countries will help increase agricultural productivity and improve food security. This paper attempts to trace the effects of IPRs on private investment in crop genetic improvement and, in turn, on agricultural productivity. The paper focuses specifically on the case of India, the regional leader in implementing IPRs in agriculture.

The paper also provides public policymakers and industry decision makers in South Asia—particularly those engaged in coordinated efforts to improve agricultural productivity—with insights into the accumulated evidence on the relationships between IPR regimes, private R&D investment, and productivity growth. It also presents several policy options worth pursuing in the future as the range of technological opportunities in agriculture expands.

The paper is organized as follows. Section 2 defines key terms and concepts relating to IPRs, including a brief description of different forms of IPRs in agriculture. Section 3 examines empirical evidence on the relationships between IPRs, private R&D investment, and agricultural productivity growth. Section 4 describes the IPR landscape in India and the structure of the country's seed industry. Section 5 presents an empirical analysis of the relationships between IPR regime, private R&D investment, and productivity growth in India. Policy recommendations and concluding remarks are offered in sections 6 and 7.

2. KEY TERMS AND CONCEPTS

This section defines and describes *intellectual property rights* in its broadest sense, followed by a discussion of legal and biological IPR mechanisms applied to agriculture. Illustrations of these different mechanisms draw primarily on examples from the United States and Europe since they were among the first to introduce IPRs in agriculture, and since their IPR systems serve as models that are currently being replicated or adapted to the needs of developing-country agriculture.

Intellectual Property Rights in Agriculture

IPRs are economic institutions designed to address inherent market failures that disincentivize investment in innovative activity (Scherer 2005). They are, in essence, a set of rules applicable to situations where private innovators will otherwise underinvest in producing a socially desirable good or service because it is simultaneously nonexcludable (that is, an individual or firm cannot be effectively excluded from using the good or service) and nonrival (that is, the consumption or use of the good or service by one individual or firm does not reduce its availability for consumption or use by others). IPRs give innovators a means to prevent unauthorized copying of their work. In effect, this legal right gives the innovator a degree of market power over her innovation, thus allowing her to accumulate extraordinary profits and recoup her investment in R&D. An innovator may choose to accumulate such profits by maintaining exclusive rights over the innovation's sale or by licensing the innovation to other parties in exchange for some form of remuneration.

An efficient and effective IPR regime is one that balances individual incentives and benefits with the wider needs of society. Thus, IPR regimes must be designed not only to encourage innovation, but also to counteract the economic losses associated with market power—the losses to consumers that result from innovators' prices that may exceed the market equilibrium, and the associated deadweight losses. This is why many forms of IPRs are granted only temporarily (optimally, for a duration that allows innovators to recoup their R&D investment) and only when a full description of the invention is filed with the issuing authority and made available in the public domain so that other innovators (and imitators) may use the invention without cost once the IPR has expired. Additionally, information in patent applications allows others the opportunity to "invent around" existing patented inventions, generating additional non-infringing approaches.

IPRs are not the only means of encouraging private investment in R&D. A separate class of mechanisms used to encourage such investment does so by reducing the cost of conducting R&D and developing new products. Such "push" mechanisms (or supply incentives) include public investment in upstream or basic research, public research grants, public subsidies on R&D input costs, tax reductions and exemptions for R&D inputs and capital equipment, or programs designed to lower the costs of meeting regulatory requirements and managing product liability (Naseem, Spielman, and Omamo 2010).

IPRs, on the other hand, are "pull" mechanisms that encourage private R&D investment by creating more efficient, more stable, or larger markets by increasing the expected returns to or reducing the risks of R&D (Naseem, Spielman, and Omamo 2010). Pull mechanisms (or demand incentives) typically reward private R&D investments by granting monopoly control over R&D outputs, increasing market opportunities through trade, and providing outright payments through advanced purchase agreements, rewards, or prizes.

Pull mechanisms are an attractive option for policymakers because they rarely require ex ante resource commitments, instead rewarding innovators for successful R&D outcomes. However, because IPRs are a strictly "negative" right—the innovator can only secure his or her right by preventing others from using the protected invention and, in the case of infringement, by seeking legal recourse with a competent authority—IPR regimes typically require public investment in the establishment and maintenance of effective regulatory and judicial systems.

Whereas IPRs are a well-established institution in the manufacturing sector, their application to agriculture is still evolving. The key issue in the agricultural sector is, quite simply, that some agricultural innovations are imperfectly appropriable. For example, plant breeders often find it difficult to prevent other breeders from imitating their work—for example, the improvement of an open- or self-pollinated crop variety such as maize, rice, or wheat. They may also find it difficult to prevent farmers from saving grain from harvest and using that grain as seed in the subsequent season, without remunerating the breeder who provided the original variety improvements. This imperfect appropriability may reduce innovators' incentive to invest in the improvement of such crops.

Several forms of IPRs employed in the agricultural sector attempt to address this issue. Legal mechanisms include patents, plant variety protection, trademarks, trade secrecy rights, and plant breeders' rights, among others. Biological mechanisms include hybridization and genetic use restriction technologies (GURTs). These legal and biological mechanisms are reviewed in the following paragraphs and summarized in Table 1.

Legal IPR Mechanisms

Plant Patents

Although patents are the most common form of IPRs in the manufacturing sector, most countries disallow patenting of plants for economic security reasons—for example, concerns that temporary market power may disrupt food supplies, food prices, or national food security. Despite this reasoning, the United States became the first country to specifically allow such patenting under the Plant Patent Act (PPA) of 1930. The PPA specifically provides 20-year patent protection for inventions derived from asexually (but nontuber propagated) reproduced varieties, implying that the patentable invention is an exact genetic replica of its parents (Fernandez-Cornejo 2004; Fuglie et al. 1996). These types of patents are particularly applicable to horticulture and floriculture, where nontuber asexual propagation is common.

Plant patents under the PPA are issued for inventions that encompass the entire plant in question. Due to this aspect, infringement can occur only if the innovator can demonstrate that an imitator has derived a plant directly from the patented plant through asexual propagation. This means that an imitator who is able to propagate the patented plant independent of the patent owner's stock cannot be held accountable for infringement. In effect, this limits the importance of plant patents in the United States, and in other countries where they have been subsequently replicated.

Plant Variety Protection

Plant variety protection (PVP) is a patent-like system that allows an owner/innovator to prohibit specific unauthorized uses of his or her invention. European nations were the first countries to leverage PVPs as an incentive mechanism for agricultural innovation under the auspices of the International Convention for the Protection of New Varieties of Plants (UPOV, established in 1961 and revised in 1972, 1978, and 1991). The 1991 UPOV Act provides 30 years of protection for trees and vines, and 25 years of protection for all other varieties. The UPOV framework, when adapted into a national legal system, offers protection for plant "varieties" (a term open to debate) that are new, distinct, uniform, and stable. These rights extend not only to the variety and its propagating materials but also to "harvested materials, including entire plants or parts of plants."

Whereas PVP legislation does grant exclusive rights to the owner/innovator, it also contains provisions that allow other innovators to use the protected materials for research purposes (called "breeders' rights" or "research exemptions") and farmers to save seed for planting in subsequent seasons (called "farmers' privilege").

Breeders' rights allow access to protected varieties for breeding and research purposes. Due to the sequential nature of plant breeding wherein the best attributes of existing varieties are combined to produce new varieties that express the best attributes of the parents, breeders' rights are considered critical to ensuring continuous cultivar improvement. However, breeders' rights also tend to disincentivize innovation because they provide competitors with fairly early access to an innovation and thus the material needed to improve on that innovation further.

Farmers' privilege allows farmers' to re-use seeds of protected varieties. Under the UPOV 1978 Act, the scope of PVP does not include farm-saved seeds. However, under the UPOV 1991 revisions, farmers' privilege became a national option and a nation may allow farmers' privilege as an exception under certain circumstances. For example, in the European Union small-scale farmers do not pay royalty whereas large-scale farmers pay royalty (usually 50 percent of normal rate) for the re-use of seeds of protected varieties. In the United States, the revisions disallowed exchange of seeds between farmers), but farmers can re-use seeds for their own use.

Revisions to the UPOV Act in 1991 aimed to strengthen breeders' rights by addressing this and other disincentives implicit in the act's earlier version (Kolady and Lesser 2010). First, the scope of the breeders' rights was expanded to include the harvested material and also the products out of the harvested material at the expense of farmers' privilege. Second, the revisions introduced a distinction between initial varieties developed by breeders and "essentially derived" varieties that integrate only slight alterations in the initial variety and therefore cannot be sold without permission of the initial variety's owner/innovator. Third, the revisions allowed farmers' privilege as a national option, such that different countries could choose different levels of privilege for their farmers.

In effect, the breeders' rights and farmers' privilege provisions imply that UPOV-style PVPs are a potentially weak form of IPR protection. In the United States, this implication was strengthened by the Supreme Court judgment in the case of *J. E. M. Ag Supply Inc. v. Pioneer Hi-Bred Int'l, Inc.* (2001) indicating that seeds are, in fact, patentable inventions.

Utility Patents

Utility patents became a means of protecting biological innovations in the United States with the U.S. Supreme Court *Diamond v. Chakrabatry* decision in 1980 that declared "anything under the sun which is made by man" to potentially be patentable subject matter. An applicant variety must be new (novel), be nonobvious (similar to distinctness), have utility (a criteria not required for PVP), and be subjected to examination. Deposits of the innovation with the competent authority are typically required and are made publicly available, although imitation is limited insofar as breeders' rights and farmers' privilege do not apply to utility patents. Due to these factors, patent protection is viewed as providing notably stronger protection than PVP. Even though patents for plant varieties are granted only in the United States, South Korea, Japan, and Australia, biotechnology patents (that is, patents on genes, processes, and so on) are granted in many countries, both industrialized and developing. For example, patenting of the Roundup Ready™ herbicide-tolerance trait in the United States allowed private firms to prevent farmers from saving and multiplying soybean seed containing the patented trait.

In order to address the concerns regarding the role of utility patents in limiting the entry to plant breeding by restricting access to germplasm, Lesser (2009) proposes a two-tier system of protection for plants where plant breeding leads to annual incremental improvements interspersed by occasional major advancements. The study proposes using the existing PVP system as the lower level of protection (while requiring farmers to pay reasonable royalties on saved seeds, and using utility patents based on functional non-obviousness standards as the higher level.

Trademarks

A trademark is an indicator used to denote the source or origin of a good or service, and implicitly provides the consumer with a warrant of the quality of the good or service bearing the mark. Legal protection is provided for trademarks through a system of registration. Both public research organizations and private companies can use trademarks to identify and protect their innovations. For example, seed companies can market their products under a brand name to create brand recognition among consumers, capture greater market share, distinguish their product from those of imitators, and bar the entry of imitators. However, while patents, PVPs, and utility patents are seen as intellectual property (IP) protection mechanisms that are essential to a firm's R&D strategy, trademarks are more commonly viewed as part of a firm's marketing strategy (Louwaars et al. 2005).

Trade Secrecy Laws

Trade secrets, in contrast to the aforementioned legal mechanisms, are not a registered form of IP protection, and are of unlimited duration as long as the holder of the trade secret makes reasonable efforts to maintain the secrecy. Quite simply, they apply where an innovator holds some information that is essential to his or her business and can demonstrate that he or she has made reasonable efforts to maintain its secrecy. Trade secrecy laws are applied most often in the case of hybrids, where the identification of the hybrid's parental lines is considered a trade secret belonging to the innovator (Moschini 2001). Thus, in the 1994 Pioneer Hi-Bred v. Holden Foundation Seeds case, an Iowa court ruled that Pioneer's use of a private coding system to identify fields of maize parent lines constituted a reasonable effort to maintain secrecy. This ruling set precedent for prosecution of imitators who attempt to steal parental lines—a practice commonly referred to as "flashlight breeding" theft. However, it should be noted here that parental lines kept as trade secrets may never become available to competitors and farmers, unlike the case of patents or PVP, where protection lasts only for a limited period.

Biological IPR Mechanisms

Hybridization

Hybrids are the key form of biological IPR in agriculture. Because the yield gains conferred by heterosis tend to decline dramatically after the first generation (F1) of seed, farmers must purchase new F1 seed each season to continually capture such yield gains. Thus the breeder who develops a hybrid (or the firm for which he or she works) is better able to appropriate the gains from innovation and recoup the R&D investment costs compared with self- or open-pollinated varieties.

In essence, hybridization prevents farmers from saving seed for their own use or selling the seed to their neighbors, a practice that farmers can do with self- or open-pollinated varieties as a matter of convention in many developing countries or under the protection of farmers' rights laws in other countries. Since farmers cannot produce their own hybrid seed without access to significant volumes of inbred parent seed, private firms provide significant value in the form of increased hybrid yields. However, hybridization does not necessarily provide protection for developers of new hybrids from competitors who can access parent seed in various ways and then sell "look-alike" hybrids. To prevent this type of misallocation, seed companies require legal IP protection, adequate analytical techniques (for example, molecular markers) to trace the origins of imposters and counterfeits, and effective enforcement in the form of legal recourse for misallocated material.

Evidence from the United States suggests that for hybridized crops such as sorghum and maize, firms capture 35 to 48 percent of the gains from improved seeds. For nonhybrid crops such as wheat, soybean, and cotton (cotton was largely a varietal crop in the United States at the time of the study), firms' share of the yield gains are lower, on the order of 12 to 24 percent (Fuglie et al. 1996). Relatedly, the greater appropriability associated with hybrids influences the level of spending that firms reinvest into R&D. Evidence from the United States suggests that firms invested more than 10 percent of seed sales into R&D for hybrid seed, while the corresponding figure was 4–5 percent for firms producing nonhybrid seed (Fuglie et al. 1996).

Genetic Use Restriction Technologies (GURTs)

Recent advances in genetics have made it possible to limit seed usage by farmers in different ways. A technology known as V-GURT, for example, renders the subsequent generation of seed sterile, thus preventing farmers from saving seed without remuneration to the innovator. Similarly, T-GURT restricts the use of a particular trait integrated into the seed such that expression of the trait can only be turned on by the external application of a (usually, chemical) inducer, thus requiring farmers to purchase the seed-cum-inducer package from the innovator.

To date, none of these GURT technologies are in commercial application due to controversies over their potential impact on biodiversity, farmers' rights, industry competitiveness, and other concerns, and most companies have placed a moratorium on development (FAO 2001). However, were they to be commercialized, their application would open up an entirely new means of IPR protection without the time and territorial limitations associated with legal IPR mechanisms.

Table 1. Forms of IPRs used in agriculture

Form of IPR	Example	Focus crops/products	Year (country)
Technology (hybrids)[a]	Hybrids	Sexually propagated plants	1920 (U.S.A.)
Plant patents	U.S. Plant Patent Act	Asexually propagated plants	1930 (U.S.A.)
Plant variety protection	Plant Variety Protection Act	Sexually propagated plants[b]	1970 (U.S.A.)
Utility patents	U.S. Patent Act	Microorganisms	1980 (U.S.A.)
		Plants	1985 (U.S.A.)
		Animals	1987 (U.S.A.)
Trade secret law	U.S. Uniform Trade Secrets Act	Parental lines of hybrids	1994 (U.S.A.)
Technology	Genetic use restriction technology (GURT)	Genetic modification technology/crops	1998 (U.S.A.)

Source: Authors; Fernandez-Cornejo (2004); Fuglie et al. (1996); Shi (2006).
Note: [a] Hybrids of maize, sorghum, and wheat were developed in 1920, 1952, and 1968, respectively.
[b] Hybrids became eligible for protection in the United States in 1985.

3. IPRS, PRIVATE INVESTMENT, AND PRODUCTIVITY GROWTH

Evidence of the declining growth rate in public spending on agricultural R&D in developing countries described by Pardey, Alston, and Piggot (2006), and the relatively limited growth of private R&D investment to make up for these declines, suggests a grim future for agricultural innovation. Arguably, one reason for low rates of investment growth may be the near absence of mechanisms that ensure appropriability of the value created by innovators.

To be sure, there is a dense literature on the impact of IPRs on agricultural innovation, especially with respect to plant breeding and cultivar improvement conducted by the private sector (Caswell, Fuglie, and Klotz 1994; Fuglie et al. 1996; Nottenburg, Pardey, and Wright 2001). Wright (1983) and Moschini and Yerokhin (2007) go so far as to develop theoretical models that identify the conditions under which different forms of IPRs (and other mechanisms) provide optimal incentives for innovation.

However, the significance and magnitude of such incentive effects remain an empirical and highly context-specific question, which requires the analyst to disentangle the incentive effects from equally important factors that disincentivize private R&D investment in developing-country agriculture—for example, small market sizes, fragmented market infrastructure, high transaction costs, and low purchasing power among end users.

This section examines prior work on the relationships that are central to answering this question. It begins with a review of the literature on the impact of IPRs on investment in crop genetic improvement, followed by a review of the literature on the impact of IPRs on productivity growth in agriculture. Note that a discussion of the literature on IPRs in Indian agriculture is held over to the next section following a more in-depth examination of IPRs and related policies in India.

IPRs and Private Investment in Crop Genetic Improvement

The studies that establish a link between IPRs and investment in crop genetic improvement tend to focus on the impact of the U.S. Plant Variety Protection Act (1970) on private investment in plant breeding and the number of varieties produced as a result of this investment.

For example, Perrin, Kunnings, and Ihnen (1983) surveyed all known seed companies in the United States and found that private investment in cereal breeding rose from just $8,000 in 1960 to $4.3 million in 1979, with a similar trend in investment per dollar of sales. Butler and Marion (1985) also examined the impact of the U.S. PVP Act and concluded that although the act had stimulated growth in the number of firms investing in plant breeding and in introduction of new soybean and wheat varieties, its impact was still fairly limited.

Foster and Perrin (1991) found somewhat greater evidence of impact. They reported that private soybean-breeding programs grew from just one program in 1970 to 34 in 1988, and PhD-level breeders in private soybean and wheat programs grew from six in 1970 to 70 in 1988. They also found that PVP certificates issued for soybean and wheat accounted for the largest number of total certificates issued between 1970 and 1987. Similarly, Frey (1996) reported that by 1994 (24 years after the U.S. PVP Act came into effect) the number of cereal breeders in the country had risen to 892, of which almost 80 percent worked in the private sector. For wheat alone, the number of breeders had risen to 130, of which 42 percent were employed by the private sector.

Alston and Venner (2000) also examined the U.S. PVP Act and its impact on wheat breeding in particular. They found that the PVP Act did not result in an increase in private investment in wheat breeding, although it did result in an increase in the proportion of private varieties cultivated in the United States, from 3 percent in the 1970s to 30 percent in the 1990s. They argued that although the PVP Act did not change investment trends significantly, it did provide private firms with a new means of differentiating and marketing their products.

There is far less literature that examines the relationship between IPRs and private investment in crop genetic improvement beyond the U.S. PVP Act. An exception to this is Pray (1992), who found that PVPs (or incentives similar to PVPs) have had some degree of impact on private R&D investment in the

United States, the United Kingdom, France, and Argentina, but with considerable variation across crops, and, in the case of Chile, no impact at all.

Eaton, Tripp, and Louwaars (2006) found that PVP encouraged private investment in rice breeding in Colombia. However, analyzing the experience of Colombia, Argentina, China, India, and Kenya, Louwaars et al. (2005) and Tripp, Louwaars, and Eaton (2007) argue that PVP should be seen as part of a broader strategy for the development of the commercial seed sector. The authors argue that in developing countries where formal seed systems are just emerging, the efficient and transparent management of regulations for seed marketing, variety registration, and seed certification and quality control encourage commercial seed development more than the establishment of PVP.

In short, the evidence provides a mixed picture of the relationship between IPRs and private investment in crop genetic improvement. As Naseem, Spielman, and Omamo (2010) explain, the evidence suggests that IPRs are a necessary, but not sufficient, condition for encouraging private investment in R&D.

IPRs and Agricultural Productivity Growth

An even more difficult relationship to establish is the one between IPRs and agricultural productivity growth. Here, issues of methodology and data sources become particularly important.

For example, Perrin, Kunnings, and Ihnen (1983) evaluated soybean variety yields between 1960 and 1979 to identify the influence of the U.S. PVP Act. The data were drawn from variety trial data from North Carolina, Louisiana, and Iowa, and the estimation was based on a hinge function (at 1970) that allowed for a comparison of the trend in yield improvement before and after the 1970 act. The authors concluded that the direction of change was consistent with the improvement in IPR protection and would have a cumulative effect over time.

Meanwhile, Babcock and Foster (1991) used variety trial data to examine the effect of PVP on tobacco variety releases and yields in North Carolina over the period 1954–1987, and found no evidence that tobacco breeders had increased the number of varieties released or developed higher-yielding tobacco varieties in response to the 1970 act.

Alston and Venner (2002) used variety trial data to evaluate the effects of PVP on wheat genetic productivity. Their dataset contained more than 20,000 observations for both hard red spring and hard red winter wheat, included data from nine U.S. states, and covered the years 1950 to 1993. Drawing on the results of several different estimation models, the authors concluded that there was “no discernable effect” of PVP on wheat yields.

Kolady and Lesser (2009) used variety trial data to evaluate the impact of PVP on wheat yields in Washington State. Their findings suggested that PVP did, in fact, promote higher yield gains through the release and cultivation of higher-yielding private varieties.

Carew and Devadoss (2003) quantified the contribution of plant breeders’ rights and transgenic varieties to canola yields in Manitoba. The results provide some limited support for a positive effect of PVP on canola yields, but mostly serve to emphasize the extensive data needs for a careful production function analysis for crops planted over wide areas with varying localized conditions. Naseem, Oehmke, and Schimmelpfennig (2005) estimated a production function to evaluate cotton improvement under PVP legislation and concluded that PVP had led to the development of more varieties and that those varieties had an overall positive impact on cotton yields in the United States.

In estimating a similar production function to analyze the factors influencing wheat yield in Manitoba, Carew, Smith, and Grant (2009) showed that varieties protected under the country’s Plant Breeders Rights Act of 1990 had a small but positive impact on yields, although yield variance was higher with greater use of protected cultivars, possibly indicating a trade-off between yield gains and yield stability.

Beyond the United States and Canada, however, similarly rigorous studies are extremely limited. One exception is Jaffé and van Wijk (1995), who found evidence of the improved performance of new, protected varieties in crops such as wheat and soybean in Argentina.

In addition to incentivizing private investment, IPRs can facilitate rapid movement of germplasm, a critical component in plant breeding and crop improvement. For example, implementation of PVP in Kenya in 1997 increased introduction of foreign germplasm especially for horticulture crops, which allowed Kenyan breeders to develop better varieties and led to the development of a competent and vibrant flower industry in Kenya (UPOV 2005). Positive effects of PVP on technology transfer between public and private sectors, both at national and international level, are also reported from countries such as Poland and Korea (UPOV 2005). Similarly, biological IPRs can play a role in wide and timely dissemination of improved seeds, especially by the private sector, which may also lead to increased productivity in farmers' fields. However, studies examining these roles of IPR which indirectly influences agricultural productivity are limited.

Thus, the evidence again provides a mixed picture. There is some evidence to suggest that IPRs and agricultural productivity are related, but findings tend to be country- and crop-specific, and tend to depend significantly on (a) the methods used to test these hypothetical relationships and (b) the type and quality of the data.

4. SEED INDUSTRY POLICY, INTELLECTUAL PROPERTY RIGHTS, AND AGRICULTURE IN INDIA

India's experience with intellectual property rights and agriculture is closely tied to the country's seed industry, which has evolved since the mid-1960s from a system of state-owned seed enterprises, research centers, and regulatory agencies to a system that now includes highly competitive foreign and domestic firms, rapidly expanding market opportunities, increasingly complex regulatory systems, and a range of new technology opportunities. The key policies that contributed to the transformation of India's seed industry, including policies on IPRs, are detailed here and summarized in Table 2.

Seed Industry Policy

India's formal seed industry was effectively launched with the introduction of the Seeds Act in 1966, a policy that gave statutory backing to a system designed to govern, manage, and regulate the production and distribution of seed for key food security crops. The industry operated through state monopolies and state certification agencies that relied primarily on publicly developed open-pollinated varieties, particularly modern rice and wheat varieties. Launch of the World Bank–aided National Seeds Project in three phases (1977–1978, 1978–1979, and 1990–1991) promoted the availability of high-quality, high-yielding variety seeds in India. Establishment of state seed corporations under the project further strengthened the seed infrastructure in the country and contributed to shaping an organized seed industry.

In 1983, the Seed Control Order began regulating private seed production and distribution by bringing seed under the umbrella of the Essential Commodities Act of 1955, which provides for the control of the production, supply, and distribution of and trade in certain commodities including rice, wheat, pulses, and oilseeds. In applying the Essential Commodities Act to seed, the government required seed dealers to obtain licenses and introduced regulations over the trade in seeds of non-notified varieties and hybrids conducted by the private sector.[1]

It was not until the late 1980s that the state's control over the seed industry began to loosen. The Industrial Licensing Policy of 1987 dereserved the seed industry, thus permitting large Indian companies (including companies having not more than 40 percent foreign ownership) to produce and market seeds in India. In 1988, the Indian government introduced the New Policy for Seed Development, a reform that led to significant change in the structure and regulation of the country's seed industry (Ramaswami 2002). The policy relaxed seed trade norms within the country; reduced import restrictions on germplasm, seed, and seed-processing equipment; and encouraged foreign company participation in the seed industry. The policy opened the door for private investment in high-value hybrids for vegetables, cereals, and cotton. The New Industrial Policy of 1991 further relaxed restrictions over India's seed industry by permitting foreign direct investment and technology transfers, while the Export and Import Policy of 2002–2007 lifted the restrictions on exports of all cultivated (other than wild varieties) seeds except for jute and onion.

The National Seeds Policy of 2002 emphasizes a regulatory framework ensuring quality seeds while facilitating a vibrant and responsible seed industry. As part of that policy, the government plans to increase India's current less than 1 percent share in the global seed trade to 10 percent by the year 2020 by establishing and strengthening Seeds Export Promotion Zones (AGRICOOP 2002). The proposed Seeds Bill of 2004 (currently under review in parliament) aims to further regulate the quality of marketed seed in India and replaces the Seeds Act of 1966 and Seed Control Order of 1983. The salient features of the proposed bill include mandatory registration of all varieties; registration of seed producers, dealers, and horticulture nurseries; self-certification of seeds by accredited agencies; compensation to farmers for underperformance of registered seeds; and penalties for selling substandard seeds and for giving false information.

[1] Notified varieties are those varieties released at the central or state level and registered with the government.

The National Food Security Mission launched in 2007 aims to increase production of rice, wheat, and pulses in India. Whereas the strategies of the mission include area expansion and productivity enhancements for wheat and pulses, no area expansion is planned for rice. Instead, for rice, the mission promotes productivity-enhancing technologies such as hybrid rice and a system of rice intensification. As part of the mission, assistance will be given for the purchase of pump sets in wheat production and sprinkler sets in pulse production in the implementing districts (AGRICOOP 2007).

Biodiversity Policy

During this same period, issues related to biodiversity emerged in the Indian policy discourse and among policymakers. India, being a party to the United Nations Convention on Biological Diversity (CBD), passed the Biodiversity Act in 2002. That act provides provisions for regulated access to biological resources by end users for various purposes, including scientific research and commercial activities. Some of the provisions of the Biodiversity Act affect seed trade and regulate transborder movement of germplasm and prerelease seed. Under the act, a National Biodiversity Authority (NBA) was established in 2003. NBA is responsible for decisions pertaining to germplasm access and benefits sharing, as well as approval for access to and transfer of biological resources or results to foreign citizens, companies, or nonresident Indians. Also, since 2002, India has been a party to the International Treaty on Plant Genetic Resources for Food and Agriculture, which, in harmony with the CBD, aims at the conservation and sustainable use of plant genetic resources for food and agriculture and the fair and equitable sharing of benefits arising out of their use. How these regulations affect germplasm exchange, a key component in the R&D of new varieties, and private R&D investment for crop improvement is still a debatable topic.

IPR Policy

Intellectual property rights became a concern in Indian agriculture and in the seed industry when India joined the World Trade Organization (WTO) in 1995 and signed on to WTO’s Trade-Related Aspects of Intellectual Property Rights (TRIPS) agreement. Article 27.3(b) requires signatory countries to provide protection for plants in the form of patents or a system created specifically for the purpose (“sui generis”), or a combination of both.

In 2001, in line with the TRIPS guidelines, the government passed the Protection of Plant Varieties and Farmers’ Rights Act (PPV&FR Act) with the objective of (1) providing an effective system for protection of plant varieties; (2) protecting the rights of farmers and plant breeders; (3) encouraging the development of new varieties of plants; (4) stimulating R&D investment and seed industry growth; and (5) ensuring the availability of high-quality seeds and planting materials to farmers. The PPV&FR Act provides for protection of novel and extant varieties.[2]

[2] A large number of popular, high-performing varieties of crops notified under the Seeds Act of 1966 continue to be marketed by different agencies. To provide legal protection to these varieties retrospectively, the PPV&FR Act has provisions for their registration within three years of crop notification in the gazette for variety registration for the remaining period. The Extant Variety Recommendation Committee advises the registrar on the suitability of these varieties for registration. Three types of extant varieties are permitted for certification: (1) varieties notified under the Seeds Act of 1966 that have not completed a 15-year (for annual crops) or 18-year (for biennials and perennials) period; (2) varieties of common knowledge; and (3) farmers’ varieties.

Table 2. Important policy initiatives in the Indian seed sector

Policy (year)	Description
Seed industry	
Seeds Act (1966)	Established variety release, seed certification, and testing systems and established state monopoly over seed production and distribution for important food crops.
National Seeds Project (1977–1991)	Led to the formation of state seed corporations and strengthened the seed system infrastructure in the country.
Seed Control Order (1983)	Regulated seed dealers through dealer licensing.
Industrial Licensing Policy (1987)	Dereserved Indian seed industry permitting private companies to produce and market seeds.
New Policy on Seed Development (1988)	Permitted import of germplasm for research, import of commercial vegetable seed, and conditional import of seeds for coarse grains, pulses, and millets.
New Industrial Policy (1991)	Permitted foreign direct investment in the seed industry.
Export and Import Policy (2002–2007)	Permitted seed importation and exportation for most of the cultivated species.
National Seeds Policy (2002)	Introduced a stronger regulatory framework for the seed industry.
The Seeds Bill (2004)	Proposes mandatory registration of all varieties and replaces the Seeds Act of 1966 and the Seed Control Order of 1983.
National Food Security Mission (2007)	Provides incentives for quality seeds of high-yielding varieties and hybrids of rice and promotes new varieties through distribution of mini seed kits.
Biodiversity policy	
Biodiversity Act (2002)	Provisions of the act deal with germplasm access and benefit sharing.
Party to International Treaty on Plant Genetic Resources for Food and Agriculture (2002)	The treaty aims at the conservation and sustainable use of plant genetic resources for food and agriculture.
IPR policy	
Protection of Plant Varieties and Farmers' Rights Act (2001)	Provides an effective system for protection of plant varieties and incentives to strengthen the seed industry and the availability of high-quality seed for farmers.

Source: Authors.

The Impact of Policy Reforms on Innovation in India's Seed Industry

As a result of the successive policy changes since the 1960s, India's seed industry has expanded substantially (Table 3). The commercial seed market, dominated by the private sector with a private/public ratio of 76:24 measured by volume, accounted for 25 percent of the total potential seed market in 2005. The varietal seeds farmers retain from prominent food and commercial crops account for the remaining 75 percent of the seed market (Rabobank 2006). Currently, in addition to a few (five) multinational seed companies, the Indian seed market is host to an estimated 410 domestic seed companies, 10 of which can be classified as large in size, 50 as medium, and 350 as small (Kumar 2010). The top 10 companies in the private sector accounted for about 25 percent of the total volume in the private sector, and more than 80 percent of companies operated as trading companies with no research investments in 2005 (Rabobank 2006). During 2008–2009, the industry generated revenues between $1.3 billion and $1.5 billion and ranked as the world's fifth largest seed market. The market for hybrid maize, hybrid pearl millet, and hybrid rice seed alone—all of which are cereal crops where private firms predominate in production and distribution—exceeded $210 million during this same period (NSAI 2010; Rao 2008). The Indian seed industry is growing at an average rate of 12 to 13 percent per year (Rabobank 2006).

Table 3. Segmentation of Indian seed industry by crop, 2005

Crop	Market segmentation	
	Volume (%)	Value (%)
Rice	48	15
Wheat	35	8
Maize	5	3
Vegetables	3	12
Sorghum	2	2
Pearl millet	2	3
Sunflower	1	3
Cotton	1	22
Other	3	32

Source: Rabobank (2006).

Although public research organizations and state seed corporations still play a role in the industry, the private sector has grown in importance in recent decades. State seed companies are now mostly confined to distributing certified seeds in the high-volume, low-value segment of the varietal wheat, rice, pulses, and cotton seed markets. The private sector, on the other hand, is making sizable inroads in the higher-value segment of the seed market, first with the development and dissemination of vegetable hybrids, then with hybrids of sorghum and pearl millet, followed by maize, cotton, and, most recently, rice (see Morris, Singh, and Pal 1998; Pray and Ramaswami 2001; Ramaswami 2002; Gerpacio 2003; Tripp, Louwaars, and Eaton 2007).[3]

In terms of specific crops, the transformation is particularly noticeable with respect to pearl millet. Pray and Nagarajan (2009) find that as of 2005, 60 percent of the total pearl millet area was planted with more than 70 hybrids, of which at least 80 percent were hybrids from the private sector. Similarly, for maize more than 50 percent of R&D effort in India is carried out by the private sector, which supplied 70 percent of total maize hybrids in 2003 (Nikhade 2003; Joshi et al. 2005).

The private sector has not only invested heavily in new crops and technologies, but has also pursued legal IPR protection under the 2001 PPV&FR Act. In 2008–2009, 64 percent of the 460 PVP applications received by the PPV&FR Authority were from the private sector, with the remaining 36 percent from the public research system and farmers themselves. As shown in Table 4, the largest number of applications was submitted for crops where hybrids, particularly private hybrids, are predominant.

[3] In fact, several private firms also supply seed for open-pollinated varieties of many crops, including seed for improved rice and wheat. However, this high-volume, low-margin segment of the industry tends to focus more on large-scale distribution and less on research, development, and innovation.

Table 4. Applications for registration of plant varieties in India under PPV&FR Act, 2008–2009

	Number of applications received			
Crop	New varieties	Extant varieties	Farmers' varieties	Total
Cotton	111	146	-	257
Maize	13	22	-	35
Rice	12	16	2	30
Pearl millet	10	14	-	24
Sorghum	8	3	-	11
Pigeon pea	4	2	-	6
Bread wheat	3	40	-	43
Other	10	43	1	54
Total	171	286	3	460

Source: PPV&FR Authority (2009).
Note: The term varieties used here includes hybrids.

What are the key factors behind the growth of India's seed industry and, more importantly, private R&D investment in agriculture? Here, we examine the evidence on the impact of policy reforms on private investment in agricultural R&D in India.

An early study by Morris, Singh, and Pal (1998) examined the impact of policy reforms on India's maize seed industry.[4] The study used data collected from surveys of public research organizations and private maize seed companies conducted in 1994 and 1995, respectively. Their findings showed that within months of the policy reforms in the late 1980s, dozens of new companies (both Indian-owned and subsidiaries of multinationals) sprang up and began producing maize seed. The study estimated that the share of proprietary hybrids of maize increased from 0 percent in 1981 to 58 percent in 1992, with a major shift occurring from 1989 onward, while private research expanded rapidly from a similarly negligible base. In a study on the Indian seed industry, Gadwal (2003) estimated that the private sector's real investment in R&D quadrupled between 1986 and 1998.

A subsequent study on Asia's maize seed industry by Gerpacio (2003) found that because of the increased private R&D investment in maize, the annual growth rate (percent/year) of sales of private maize hybrids in India was much higher at 32.4 percent than that of the public sector (2 percent) during 1990–1998. Importantly, the study finds that the concomitant increase in maize production during this period resulted mainly from yield gains and not area expansion.

Studies by Pray, Ramaswami, and Kelley (2001) and Pray and Ramaswami (2001) provide similar insights for several other crops. Using a unique dataset that captures private seed firm activity in 1987 and 1995, these studies examined the direct and indirect quantitative effect of policy reforms of the late 1980s on private R&D investment in agriculture. The studies concentrated on hybridized crops where private R&D investment was most significant, namely cotton, maize, sunflower, sorghum, pearl millet, hybrid rice, and rapeseed/mustard (Table 5).

[4] According to the study, public breeding programs were releasing varieties and hybrids in almost equal numbers during the 1960s. However, over the following two decades, the proportion of varieties released increased due to two factors: first, the perception existed that hybrid technology is not appropriate for small farmers who cannot afford high levels of purchased inputs (a point raised in Ramaswami [2002]), and second, successful adoption of hybrids requires annual seed purchases and therefore cannot succeed without the support of a well-developed seed industry. But during the mid-1980s, attention shifted back to hybrids, mainly because of the growth of private-sector breeding programs on hybrid maize.

Table 5. Comparison of private R&D in India by crop for years 1987 and 1995

Crop	Number of firms with R&D			R&D expenditure (US$)[a]		
	1987	1995	Percentage change	1987	1995	Percentage change
Sorghum	10	27	170	216,049	648,148	200
Pearl millet	12	30	150	246,914	617,284	150
Maize	6	24	300	123,457	709,877	475
Sunflower	10	26	160	216,049	648,148	200
Cotton	9	27	200	123,457	833,333	575
Mustard	1	9	800	30,864	308,642	900
Rice	0	15	-	0	493,827	-

Source: Authors' calculation based on data reported in Pray and Ramaswami (2001).
Note: [a] Calculation based on the 1995 exchange rate of 32.4 Indian rupees (INR)/U.S. dollar.

Arguing that the policy reforms have encouraged several large firms (both foreign and domestic) to enter the industry beginning in 1987, these studies estimate that such firms accounted for about 36 percent of the increase in R&D spending between 1987 and 1995, and that R&D investment would have been $1.5 million lower in the absence of such firms.[5]

Pray and Ramaswami (2001) also found that the growth in R&D expenditure by large incumbent firms can be partially explained by the competitive pressure of new large entrants, which forced local firms to invest more in research to remain competitive, even after controlling for factors that favored growth in R&D spending by large incumbent firms, such as increased demand in domestic markets and the development of rice and rapeseed hybrids in the early 1990s. Furthermore, these studies found that the growth in R&D is partly attributable to the entry of several small firms with plant-breeding programs that had entered the industry since 1987 and focused on hybrids of pearl millet, sorghum, and cotton. Although they suggest that the entry of the small firms was driven by growth in the market for private hybrids and not by policy reforms, they also recognize that firms' breeding programs were dependent on policy reforms that improved the access and availability of breeding materials from public research organizations, from foreign firms, or through importation from other foreign sources.

Importantly, the study by Pray and Ramaswami (2001) demonstrated that policy reforms that encouraged the development and distribution of private hybrids resulted in significant increases in crop yields of pearl millet, sorghum, and maize in India's semiarid tropics. In a study analyzing the private seed industries of pearl millet and sorghum in India, Pray et al. (1991) calculated that seed companies captured 18.5 percent of the yield increase of hybrid sorghum and 6 percent of the gains from pearl millet hybrids. Conversely, Ramaswami (2002) argued that the absence of a sufficient IPR policy regime to protect parental lines of hybrids in India has forced the private sector to invest more in developing double-cross hybrids, which are more difficult to imitate but yield 10 to 15 percent less than single-cross hybrids.[6] Gerpacio (2003) echoes this concern, noting that without enforceable IPRs, many private companies may be reluctant to release their best maize hybrids because of the fear of losing proprietary control over their inbred lines.

[5] 50 million Indian rupees (INR), based on a 1995 exchange rate of 32.4 INR/U.S. dollar.

[6] Double-crosses may also be used because the female inbred parent line is too low yielding for adequate returns on some hybrids.

5. PUBLIC POLICIES, PRIVATE INVESTMENT, AND PRODUCTIVIY GROWTH: AN EMPIRICAL EXERCISE

With the exception of the studies discussed in the previous section, prior analyses of policy reforms and technological change in India have focused on their impact on private investment in agricultural R&D. Here, we take this analysis one step further by examining the impact of policy change and technological change on agricultural productivity. Specifically, we examine the impact of the 1988 National Policy on Seed Development (NPSD) and biological IPRs associated with hybridization on changes in the annual maize and pearl millet yields in India.

In effect, this empirical exercise is a demonstration of how past policy reforms and technological changes have successfully increased yields in the past, thus suggesting that similar efforts that leverage private-sector involvement can be applied to other crops—particularly rice and wheat—in the future. An empirical examination of this hypothesis is presented below.

Background: Maize, Pearl Millet, Rice, and Wheat in India

As a starting point, we briefly characterize the four main staple crops under discussion: maize, pearl millet, rice, and wheat.[7] Table 6 presents the major production statistics for those crops in India.

The maize production regions in India can be classified into two production environments: (1) traditional maize-growing areas, which include Bihar, Madhya Pradesh, Rajasthan, and Uttar Pradesh; and (2) nontraditional maize-growing areas, which include Karnataka and Andhra Pradesh. Traditional maize-growing areas account for about 60 percent of total maize area and 40 percent of total maize production in India. In traditional cultivation systems, the crop is grown primarily as a food crop, whereas in nontraditional systems, the crop is grown mainly for commercial purposes (that is, poultry feed). Maize is replacing sorghum and pearl millet as a feed and fodder crop. The unit cost of production of maize is higher in traditional maize-growing areas except in Bihar, where the moisture regime and climatic conditions favor wide adoption of improved cultivars and higher maize yields (Joshi et al. 2005).

Pearl millet is typically grown as a dual-purpose grain and fodder crop in the semiarid regions of the country. Because of the increase in per capita income, food consumption of pearl millet is declining; however, its demand for use in the poultry and animal feed sector is increasing (Pray and Nagarajan 2009). Rajasthan, Gujarat, Maharashtra, Haryana, Uttar Pradesh, Madhya Pradesh, Karnataka, Andhra Pradesh, and Tamil Nadu are the major pearl millet–producing states in India.

Rice, the largest food crop in India in terms of cultivated area and yield, is grown in five production regions: the Northeast (Assam and northeastern states); the East (eastern Uttar Pradesh, Bihar, West Bengal, Orissa, Chhattisgarh); the North (western Uttar Pradesh, Punjab, Haryana, Uttarakhand); the West (Gujarat, Maharashtra, Rajasthan); and the South (Tamil Nadu, Karnataka, Andhra Pradesh, and Kerala). Rice can be cultivated in the *kharif* (winter), *rabi* (summer), and pre-*kharif* (autumn) seasons in India, depending on the production region, agroecology, and farming system. Rice is primarily a food crop, although the straw is an important source of livestock fodder in many regions.

Wheat, the second largest food crop in India, is produced primarily in the country's northern region. The main wheat-producing states are Punjab, Haryana, Uttar Pradesh, Bihar, Madhya Pradesh, Rajasthan, and Gujarat. Winter wheat is the most important class of wheat grown in India. Like rice, wheat is primarily a food crop, but is used as a source of livestock fodder.

[7] Sorghum, an important coarse cereal in India, also benefited from the development of hybrids and policy reforms. However, as noted in Pray and Nagarajan (2009), there is a shift in production from rainy sorghum (*kharif*) to post-rainy sorghum (*rabi*). Because of that shift, the R&D focus also has changed, making the sorghum story complicated. Further, state-wise time series data for *kharif* and *rabi* sorghum are not available to capture the shift in production. Because of this, this study does not include sorghum in the current analysis.

Table 6. Production statistics of rice, wheat, maize, and pearl millet in India

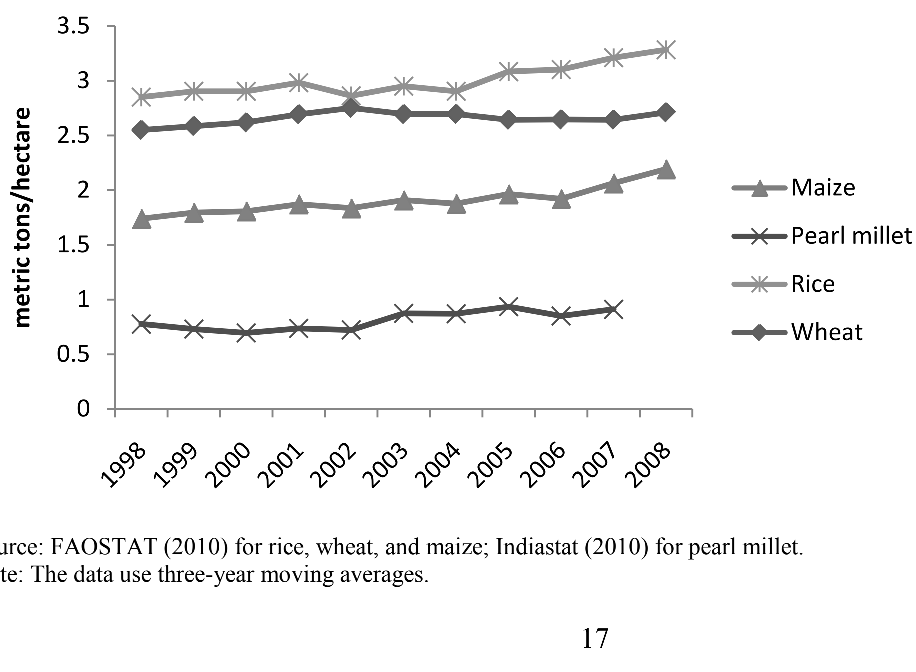
Crop	2008 harvested Area (million hectares)	2008 harvested Yield (metric tons/hectare)	Area as a % of total area under cereal cultivation (2008) (%)	Change (1998–2008) in[a] Area (%)	Change (1998–2008) in[a] Yield (%)	Seed replacement rate (2006) (%)	Share of area under hybrids (2003–2008)[b] (%)
Rice	44.0	3.37	43.7	-0.07	15.2	25.1	6.2
Wheat	28.0	2.80	27.8	6.34	6.3	18.0	-
Pearl millet[c]	9.6	1.04	9.5	-0.98	17.3	56.1	60.0
Maize	8.9	2.32	8.2	29.15	25.9	36.2	60.0

Source: FAOSTAT (2010) for area and yield data for rice, wheat, and maize, and Indiastat (2010) for area and yield for pearl millet; Seednet (2007) for seed replacement rates; and Gulia et al. (2007), Kanoi (2009), and Kumar (2010) for share of area under hybrids.
Note: [a] Three-year moving averages are used to calculate the percentage changes.
[b] Hybrid rice data given here are for 2008-2009, maize for 2008-2009, and pearl millet for 2003.
[c] Pearl millet data given here are for 2007.

The area under cultivation for each crop has shifted over the last decade. Most significant is the change in maize area due to increases in demand for livestock and poultry feed. Also significant is the (somewhat smaller) decline in area under pearl millet cultivation, which reflects the effects of consumers substituting out of millet and into other staples and nonstaples as a result of rising incomes. Meanwhile, rice area under cultivation has remained relatively stable, although wheat area has expanded (Table 6).

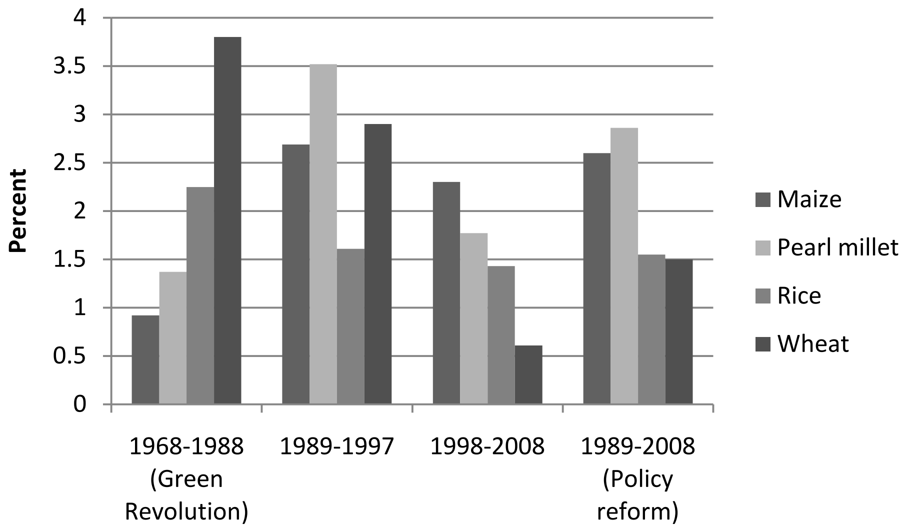
During the last decade, the changes in maize and pearl millet yields have been noticeably greater than the changes in rice and wheat yields (Table 6). Figures 1 and 2 illustrate the trends more clearly, showing that yield growth rates of maize and pearl millet have increased since 1988, with the highest growth rates during 1989–1997, but yield growth rates of rice and wheat peaked during the Green Revolution period (1968–1988) and have not recovered since.

Figure 1. Yields of maize, pearl millet, rice, and wheat, 1998–2008, India



Source: FAOSTAT (2010) for rice, wheat, and maize; Indiastat (2010) for pearl millet.
Note: The data use three-year moving averages.

Figure 2. Compound annual growth rates in yields of maize, pearl millet, rice, and wheat, 1968–2008, India



Source: Authors' calculation based on FAOSTAT (2010) for rice, wheat, and maize; Indiastat (2010) for pearl millet.
Note: The data use three-year moving averages.

There are several explanations for the relatively late (yet rapid) growth in maize and pearl millet yields, many of which have been discussed earlier. First is the contribution of public research: Although the Indian and international agricultural research systems were focused primarily on rice and wheat improvement in India during the 1970s, their subsequent investments in maize and pearl millet paid off in later time periods (Pray et al. 1991; Joshi et al. 2005). Second, and of comparable importance, is the change in India's policy environment in the mid-1980s that encouraged the entry of private companies into the seed sector. The 1987 Industry Licensing Policy and the 1988 New Policy for Seed Development (discussed earlier), combined with improved access to hybrid breeding lines for maize and pearl millet, encouraged rapid entry of private firms into the seed business for these two crops. In effect, these events converged in 1987–1988 to open up the Indian seed market and make hybrid breeding lines more readily available to private firms (Pray et al. 1991; Morris, Singh, and Pal 1998). Prior to 1988, private firms played a negligible role in the seed industry for these two crops, and private maize and pearl millet hybrids were virtually nonexistent.

Twenty years later, the outcomes of these events are readily apparent. Private companies supplied 82 percent of the total volume of high-yielding pearl millet varieties/hybrids to farmers in India in 2006–2007 (Pray and Nagarajan 2009). The private sector carries out more than 50 percent of maize R&D in India (Joshi et al. 2005).[8] Table 6 provides more decisive indicators in the form of high seed replacement rates and area under hybrids for both maize and pearl millet.[9] As might be expected, seed replacement rates of hybrid crops are much higher than those of self-pollinated crops, evidence of the higher potential for appropriability of hybrid crops.

8 According to a study by Joshi et al. (2005), whereas public-sector research on maize focused on developing composite varieties, the private sector focused on developing hybrids suitable for favorable production environments. Because of the fragile maize seed sector in the traditional maize-growing areas, benefits of maize improvement were not realized to the similar extent as they were for rice and wheat.

9 Interestingly, the seed replacement rates for rice and wheat are also high, or at least higher than the conventional wisdom might suggest for self-pollinated crops. However, according to industry sources, the seed for these crops tends to be sold by private firms or formerly public seed enterprises on a low-margin, high-volume basis, whereas hybrid maize and pearl millet seed is sold for relatively higher prices that reflect the higher costs of seed production and the demand for quality seed.

Key Hypotheses

As discussed earlier, there is ample theoretical and empirical evidence to suggest that increased potential for appropriability and excludability, either through biological or legal forms of IP protection, can lead to increased private investment in agricultural R&D (Perrin, Kunnings, and Ihnen 1983; Fuglie et al. 1996). However, what remains to be seen is whether increased private investment in crops triggered by increased appropriability (either biological or legal) has led to increases in crop productivity in developing countries. As mentioned earlier, studies on the impact of legal forms of IPRs on crop productivity in industrialized countries show mixed results, and studies in developing countries are few and far between.

Since implementation of PVP regulations in India began only in 2007, a sufficient body of data has not yet been accumulated to analyze the impact of this legal form of IPR protection on productivity. But much can be learned by drawing on experiences from the late 1980s, when policy changes opened up India's seed industry to private investment and hybrids provided private firms with a biological form of IPR regulation. Specifically, the difference in the private sector's response to the policy reforms of the late 1980s between hybrid crops (that is, maize and pearl millet) and self-pollinated crops (that is, rice and wheat) suggests that favorable policy changes combined with biological forms of IPR protection are essential to attracting private investment.

What remains to be seen is whether these factors are similarly influential in increasing productivity. The difficulty in obtaining consistent data on area under specific varieties and hybrids, ownership details of varieties and hybrids, varietal yields under farmer conditions, and so on frustrates this type of inquiry. Thus the empirical exercise undertaken here tests whether a structural change in the yield trends for these crops occurred following the passage of NPSD in 1988, evidence of which would indirectly suggest a positive response to policy reforms and technological change.

Thus, we hypothesize here that supportive policy changes and enforceable IPRs encourage greater private investment in the research, development, and delivery of improved seed, ultimately leading to increases in yields. We test this hypothesis by examining yields since 1966 for maize and pearl millet crops, and comparing them with rice and wheat to shed light on whether policy reforms and enforceable IPRs lead to faster genetic improvement and thus to faster yield growth.

The Empirical Model

The following is the general form of the empirical model used in the analysis.

$$\begin{aligned} Y_{ist} &= a_0 + a_1 PHYVAREA_{it} + a_2 PIRRIGAREA_{it} + a_3 RAINFALL_{st} + a_4 PRICE_{ist-1} + a_5 YRHARVEST_{it} \\ &+ a_6 FERTILIZERPRICE_t + a_7 STATE_{is} + a_8 DPOLICY_t + e_{ist}. \end{aligned} \tag{1}$$

In this model, the average yield of crop *i* (rice, wheat, maize, and pearl millet) in state *s* in year *t* (Y_{ist}) is determined by the variables described below.[10]

$(PHYVAREA_{it})$, which denotes the proportion of area of crop *i* under high-yield varieties (HYV) in year *t.* We include this as a proxy for public-sector R&D investment in agriculture.[11] High-yield varieties include public and private hybrids and improved open-pollinated varieties. Because of the lack of state-level data, we use national-level data in the analysis.

$(PIRRIGAREA_{it})$, which denotes the proportion of area under irrigation of crop *i* in year *t.* Because of the lack of state-level data, we use national-level data in the analysis.

$(RAINFALL_{st})$, which denotes the average annual rainfall in state *s* in year *t.*

[10] It is worth noting here that alternative dependent variables could be considered in the estimation of this model. For example, year-on-year yield differences (instead of yields) could be considered, as could differences between experimental yields and yields under farm conditions. Estimations using the former generated a poor fit to the model, while estimations of the latter suffer from an absence of state-level data. However, further investigation of these alternatives is a topic for future research.

[11] An alternative variable could be lagged values of public-sector R&D spending on agriculture. However, time series data on public R&D spending in India are available only since 1981.

($PRICE_{ist-1}$), which denotes the real farm harvest price of crop *i* in state *s* in year *t-1,* obtained by deflating the farm harvest price by the wholesale price index, using 1993–1994 as the base year. Crop-specific data on variable input use and irrigation that might influence yield are not available. However, we include lag values of real farm harvest prices as a proxy for farmers' perception on crop profitability that might influence farmers' variable input use.[12]

($YRHARVEST_{it}$), which denotes the year of harvest of crop *i* in year *t.* Year is included as a trend variable. This variable is also intended to capture any changes in the weather conditions and external shocks that might have some effects on crop yield.

($FERTILIZERPRICE_t$), which denotes the real value of fertilizer price paid by farmers for urea, one of the most commonly used fertilizer in India, in year t. Since crop and state specific data on fertilizer use which could influence yield is not available, we include real values of national level fertilizer prices in the model as that might capture changes in the amount of fertilizer (urea) used by farmers over the years.

($STATE_{is}$), which is an intercept dummy variable representing individual states.

And ($DPOLICY_t$), which is an intercept dummy variable representing the policy change associated with promulgation and implementation of NPSD in 1988.

($DPOLICY_t$) is the variable of interest insofar as it explains the structural change in yield trends. The variable is introduced into the empirical model with a lag to reflect the time required for firms to respond to NPSD and invest in plant-breeding programs and other research and commercialization activities. The size of the lag depends on assumptions made about the R&D process. For example, as a response to the NPSD regulation, if the private sector started using readily available material, it could develop a marketable product in three to five years. That is likely the historical scenario in India, where breeding lines for improved cultivars were developed by the public sector and multiplied or further improved by the private sector, indicating a relatively short lag period. Alternatively, if new materials are used for the research, it could take five to 10 years before a product is developed. That is more likely the modern scenario in India, where foreign and domestic private companies are rapidly expanding their research investments and breeding capabilities, often independently from the public sector.

To account for both such scenarios, we test the hypothesis taking both four years and six years as the research time lag. The hypothesis is tested using the intercept dummy variable ($DPOLICY_t$), which is equal to 1 for years since 1992 (under the four-year research lag scenario) or for years since 1994 (under the six-year research lag scenario).

For the purposes of this exercise, we interpret a positive and significant sign on the intercept dummy variable ($DPOLICY_t$) as suggestive of a structural change in the yield model since the passage of NPSD. Thus, we interpret a positive and significant sign on ($DPOLICY_t$) to be supporting evidence of the hypothesis that increased appropriability (policy reforms plus biological IPR) leads to increased crop productivity—that is, greater private R&D investment triggered by the 1988 NPSD led to increases in crop yield growth.

Estimations using data on maize and pearl millet yields are expected to provide model-consistent results. Estimations using data on rice and wheat, however, may provide a test of the alternative hypothesis that no structural change occurred in the yield trends around the 1988 NPSD—that is, policy reforms did not attract private R&D investment because of an absence of appropriability in either a legal or biological form of IPRs, ceteris paribus. In this scenario, a nonsignificant coefficient on the ($DPOLICY_t$) variable is seen as supporting evidence to the alternative hypothesis.

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[12] Including data on minimum support price was another option. We found positive correlation between minimum support prices and state-wise farm harvest prices. However, as suggested by Pray and Ramaswami (2001), we include farm harvest price in the model as that might capture farmers' decisions on variable input use more effectively.

Data and Data Sources

National-level data may not reflect state-level differences and effects on variables included in equation (1). Hence the estimations conducted here rely on state-level data, except for proportion of area under irrigation, real values of fertilizer price, and proportion of area under high-yield varieties, for which state-level data are not available.

A panel dataset on crop yield, rainfall, and real farm harvest prices for each crop for the period 1966 to 2007 was generated. We selected five of the top eight producing states representing different production regions for each crop. Data were collected from various sources, listed in Table 7.[13] State-wise description of the variables used for the analysis presented in Table 7 highlight the diversity in different production systems of rice, wheat, maize, and pearl millet in India.

Table 7. Production statistics of rice, wheat, maize, and pearl millet, selected Indian states, 1966–2007

State	Yield (metric tons/hectare)	Real farm harvest price (INR/metric ton)	Rainfall (millimeters)	Seed replacement rate (%) 2006[a]
Maize				
Madhya Pradesh	1.2 (0.4)	33.5 (7.3)	1013.6 (157.9)	13.0
Bihar	1.5 (0.6)	38.9 (13.1)	1068.4 (172.4)	60.0
Uttar Pradesh	1.1 (0.3)	33.8 (9.2)	1035.4 (138.9)	12.3[b]
Rajasthan	1.0 (0.3)	37.5 (9.9)	446.9 (117.9)	19.9
Andhra Pradesh	2.2 (0.9)	33.0 (7.1)	622.5 (190.2)	87.0
Pearl millet				
Madhya Pradesh	0.8 (0.3)	35.9 (10.2)	1013.6 (157.9)	55.4
Gujarat	0.9 (0.3)	43.1 (11.3)	658.6 (228.4)	-
Uttar Pradesh	0.9 (0.3)	34.6 (11.6)	1035.4 (138.9)	50.5
Rajasthan	0.3 (0.2)	38.3 (11.1)	446.9 (117.9)	46.2
Andhra Pradesh	0.7 (0.2)	33.4 (8.2)	622.5 (190.2)	67.0
Rice				
Karnataka	2.1 (0.4)	40.0 (9.8)	1414.4 (216.8)	34.0
Bihar	1.1 (0.3)	35.4 (12.8)	1068.4 (172.4)	12.0
Uttar Pradesh	1.4 (0.5)	32.2 (7.4)	1035.4 (138.9)	20.3[b]
Assam	1.2 (0.2)	35.2 (6.6)	1406.6 (159.5)	10.7
Andhra Pradesh	2.2 (0.6)	35.0 (4.9)	622.5 (190.2)	76.0
Wheat				
Madhya Pradesh	1.2 (0.4)	46.9 (8.9)	1013.6 (157.9)	13.1
Bihar	1.6 (0.4)	46.1 (15.9)	1068.4 (172.4)	11.0
Uttar Pradesh	1.9 (0.6)	42.8 (13.5)	1035.4 (138.9)	24.1
Rajasthan	1.9 (0.6)	48.1 (12.8)	446.9 (117.9)	19.1
Haryana	2.9 (0.9)	43.1 (12.3)	512.1 (152.7)	23.3

Source: Indiastat (2010) for data on area, yield, rainfall, and wholesale price index used to calculate real farm harvest price; CMIE (2010) for data on farm harvest prices; and Seednet (2007) for seed replacement rates.
Note: Standard deviations are given in parentheses.
[a] Because of the unavailability of time series data on seed replacement rate, these figures are not used in the empirical analysis. However, we report these figures in the table above to highlight state-wise differences.
[b] Data are for 2005.

[13] Data on fertilizer price (urea) paid by farmers were collected from FAOSTAT (2010).

Average maize yield in traditional maize-growing areas (Uttar Pradesh, Madhya Pradesh, and Rajasthan) is almost half that of nontraditional maize-growing areas (Andhra Pradesh). The seed replacement rate in Andhra Pradesh is much higher than that of Madhya Pradesh, Uttar Pradesh, or Rajasthan, suggesting that most maize producers in Andhra Pradesh (or nontraditional maize-growing areas) grow hybrid maize, whereas most maize producers in traditional maize-growing areas, except Bihar, grow composite varieties.

As suggested by Table 7, rice is cultivated under rainfed conditions in Bihar, Uttar Pradesh, and Assam because of relatively heavy rainfall. In Karnataka and Andhra Pradesh, rice is grown under irrigated conditions in the deltaic tracts of the Kaveri, Godavari, and Krishna rivers and under rainfed conditions in the nondeltaic tracts. Seed replacement rates are higher in Andhra Pradesh and Karnataka than in other states as rice in the former states is grown under more favorable conditions. As in the case of rice, there are considerable variations in yields and seed replacement rates for wheat between and among states.

Data presented in Table 7 highlight the state-level differences of variables included in the study. Since we include major producing states of each crop from different agroclimatic zones in India, we consider the data as nationally representative. It should be noted here that maize and pearl millet are mostly grown under rainfed conditions, whereas most of the area under wheat and rice (to some extent) is under irrigated conditions (Table 8).

Table 8. Summary of proportions of area under high-yielding varieties and irrigation for maize, pearl millet, rice, and wheat in India, 1966–2007

Crops	Proportion of area under high-yielding varieties (%)	Proportion of area under irrigation (%)
Maize	36.2	19.4
Pearl millet	47.4	5.8
Rice	51.0	45.3
Wheat	71.7	73.9

Source: Indiastat (2010).

Results

In this section we present estimation results of yield models of maize, pearl millet, rice, and wheat. Diagnostic tests were conducted to examine for the presence of nonstationarity and autocorrelation. Based on the Wooldridge test for autocorrelation in panel data, we made necessary corrections for rice and wheat estimations. To address correlation across the panel (that is, states) the panel data were estimated using the feasible generalized least squares (FGLS) method. Because of the positive and statistically significant correlation between proportion of area under high-yield varieties and proportion of area under irrigation, we include only one of them in the model specification. Results using different specifications of the model are included to test for robustness of the results. [14]

Table 9 presents the estimation results for maize yields. The positive and statistically significant coefficient on the policy change variable supports the hypothesis that yield of maize, a hybrid crop, increased since the passage of NPSD in 1988. In other words, we find a positive and significant structural change in the maize yield trends since 1988 versus prior to 1988.

[14] Models 1 to 4 vary based on the variables included and the research time lag used. For each time lag (that is four years and six years) we have two model specifications including either the irrigation variable or the HYV variable. As mentioned earlier, because of the high correlation between these two variables, we include only one of them in the specification. We tried specifications including interaction term between year of harvest and policy change variable, however the interaction term was not significant across crops. Different specifications are included to test the robustness of the results.

Table 9. Estimation results of maize yield model using panel data, 1966–2007, India

Variable	Model 1	Model 2	Model 3	Model 4
Dependent	Yield	Yield	Yield	Yield
Rainfall (millimeters)	0.0000 (0.0001)	-0.0000 (0.0000)	0.0000 (0.0000)	-0.0000 (0.0000)
Real farm harvest price($t-1$) (INR/metric ton)	0.0010 (0.0025)	0.00097 (0.0025)	0.0024 (0.0025)	0.0023 (0.0025)
Year of harvest (year)	0.0262*** (0.0079)	0.0237*** (0.0058)	0.0287*** (0.0087)	0.0272*** (0.0068)
Percentage of crop area under high-yield varieties (%)	-0.0028 (0.0049)		-0.0026 (0.0053)	
Percentage of crop area under irrigation (%)		-0.0148 (0.0100)		-0.0160 (0.0110)
Real fertilizer price (INR/metric ton)	-0.0009 (0.0015)	-0.0009 (0.0014)	-0.0016 (0.0016)	-0.0015 (0.0015)
Policy change (lagged)	0.3069*** (0.0794)	0.2867*** (0.0794)	0.1984** (0.0838)	0.1705** (0.0850)
Constant	-50.5264*** (15.5313)	-45.4544*** (11.6661)	-55.4760*** (17.2893)	-52.2786 (13.4955)
Number of observations	210	210	210	205
Policy change lag (years)	4	4	6	6
Estimation	FGLS	FGLS	FGLS	FGLS

Source: Authors.
Note: Values in parentheses denote standard errors. Coefficients are significant at the * 10 percent, ** 5 percent, and *** 1 percent levels, respectively.

We see a relatively lower statistical significance of the policy change variable with a six-year time lag; that may be because, as reported in Morris, Singh, and Pal (1998), private seed companies started producing hybrids using already available breeding materials from the public sector, making the structural change in the yield quite obvious in years immediately after 1988.

To highlight state-level differences, we present the estimation results using seemingly unrelated regression (SUR) in Table A.1 in the appendix.[15] Note the overall insignificance of the coefficient on the policy change variable in all states in traditional maize-growing areas except Bihar, where the relatively higher seed replacement rate shown in Table 7 suggests that farmers depend more on purchased seed. This finding supports findings by Joshi et al. (2005) that suggest that states in traditional maize-growing areas, except Bihar, have less favorable production environments for maize, such that yield growth is relatively slow. However, the positive coefficient of Andhra Pradesh suggests that states in nontraditional maize-growing areas, where most maize growers use hybrids, have higher maize yields. Even though there are state-level differences in yield performance, overall findings suggest that since the passage of NPSD in 1988, there has been a positive and significant structural change in the yield trends for maize.

[15] Seemingly unrelated regression (SUR) allows for cross-equation (in this case, across states) comparison in a single model. Since the diagnostic test for model specification preferred the random-effects model over the fixed-effects model, instead of pooled regression with state dummies, we use SUR to highlight the state-level differences in yield performance. Since results using proportion of area under high-yield varieties and proportion of crop area under irrigation were more or less similar, we present results using only one of them (proportion of area under high-yield varieties). Estimation results using four and six-year time lag are more or less similar. However, as mentioned earlier since we think six-year time lag in research is a more likely scenario especially for rice and wheat in India, we only present results using a six-year time lag for SUR.

We take this finding to be indirect evidence of the positive impact of favorable policy reforms and effective biological IPRs on crop productivity.

Table 10 presents the estimation results for pearl millet yields. Because of the overall lower percentage of pearl millet area under irrigation, we do not include percentage of area under irrigation in our specifications in Table 10. We again find supporting evidence of the hypothesis that there is a positive and significant structural change in the yield trends for pearl millet since 1988. The lower significance of the policy change variable with a six-year time lag compared to that of a four-year time lag is consistent with the explanation discussed earlier: private seed companies in India commercialized pearl millet hybrids using breeding materials already developed by public research organizations, thus reducing the response times to the policy reforms.

Results from estimations that isolate state-specific effects on pearl millet yields (Table A.2 in the appendix) generate a statistically significant coefficient on the policy change variable for those states with higher seed replacement rates. This is consistent with our general hypotheses and the results for maize discussed earlier.

Table 10. Estimation results of pearl millet yield model using panel data, 1966–2007, India

Variable	Model 1	Model 2
Dependent	Yield	Yield
Rainfall (millimeters)	0.0005***	0.0005***
	(0.0000)	(0.000)
Real farm harvest price($t-1$) (INR/metric ton)	0.0023*	0.0032**
	(0.0014)	(0.0014)
Year of harvest (year)	0.0146***	0.0178***
	(0.0052)	(0.0052)
Percentage of crop area under high-yield varieties (%)	-0.0015	-0.0025
	(0.0018)	(0.0019)
Real fertilizer price (INR/metric ton)	-0.0008	-0.0009
	(0.0006)	(0.0006)
Policy change (lagged)	0.1020***	0.0700**
	(0.0359)	(0.0357)
Constant	-28.5249***	-34.9226***
	(10.3612)	(10.2598)
Number of observations	210	210
Policy change lag (years)	4	6
Estimation	FGLS	FGLS

Source: Authors.
Note: Values in parentheses denote standard errors. Coefficients are significant at the * 10 percent, ** 5 percent, and *** 1 percent levels, respectively.

These findings suggest that as in the case of maize (a hybrid crop) there is a positive and statistically significant structural change in the yield model of pearl millet, a hybrid crop, since the passage of NPSD in 1988. We take the positive and statistically significant coefficients on the policy change variables for maize and pearl millet yield trends as supporting evidence of the hypothesis that the yield growth of hybrid crops with a greater potential for appropriation was higher since 1988. The continued private investment in semiarid crops such as maize and pearl millet might be one of the reasons for relatively higher annual growth rates in yields of maize and pearl millet compared with those of rice and wheat during the last decade (Figure 2). Here, we take hybridization within the context of NPSD implementation as a proxy for the scenario of enforceable IPR regulation. Supportive evidence of the hypothesis suggests that enforceable IPR protection can have a positive effect on crop productivity.

Estimation results for rice yields are presented in Table 11. The insignificant coefficient on the policy change variable with both four- and six-year lags lends support to the hypothesis that because of the lack of appropriability for rice, there was no structural change in yield trends for self-pollinated crops following the 1988 NPSD.

Table 11. Estimation results of rice yield model using panel data, 1966–2007, India

Variable	Model 1	Model 2	Model 3	Model 4
Dependent	Yield	Yield	Yield	Yield
Rainfall (millimeters)	0.0002***	0.0002***	0.0002***	0.0002***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Real farm harvest price($t-1$) (INR/metric ton)	0.0008***	0.0076***	0.0080***	0.0078***
	(0.0028)	(0.0028)	(0.0028)	(0.0028)
Year of harvest (year)	0.0280***	0.0434***	0.0315***	0.0448***
	(0.010)	(0.0076)	(0.0102)	(0.0075)
Percentage of crop area under high-yield varieties (%)	0.0059		0.0055	
	(0.0047)		(0.0047)	
Percentage of crop area under irrigation (%)		-0.0093		-0.0072
		(0.0121)		(0.0122)
Real fertilizer price (INR/metric ton)	-0.0002	-0.0003	-0.0002	-0.0002
	(0.0009)	(0.0009)	(0.0009)	(0.0009)
Policy change (lagged)	0.0077	0.0044	-0.0913	-0.0819
	(0.0937)	(0.0984)	(0.0907)	(0.0970)
Constant	-55.0360***	-84.7861***	-61.7920***	-87.6257***
	(20.4412)	(14.7598)	(20.0608)	(14.668)
Number of observations	210	210	210	210
Policy change lag (years)	4	4	6	6
Estimation	FGLS	FGLS	FGLS	FGLS

Source: Authors.
Note: Values in parentheses denote standard errors. Coefficients are significant at the * 10 percent, ** 5 percent, and *** 1 percent levels, respectively.

Results shown in Table A.3 in the appendix highlight the state-level differences in the yield performance of rice. The policy change variable is insignificant across states.

We consider the insignificant coefficient on the policy change variable for rice yield (compared with the significant coefficients for the maize and pearl millet yield trends) as evidence in support of the hypothesis that policy reforms without provisions for IPR protection (either biological or legal) do not attract private R&D investment and thus have a negligible effect on productivity growth.

Turning to the case of wheat yields, we find results that are similar to those for rice. The statistically insignificant coefficient on the policy change variable (Table 12) supports the hypothesis that because of nonappropriability, there was no structural change in wheat yield trends following 1988's NPSD. Results in the appendix's Table A.4 highlight the state-level differences in the yield performance.

Table 12. Estimation results of wheat yield model using panel data, 1966–2007, India

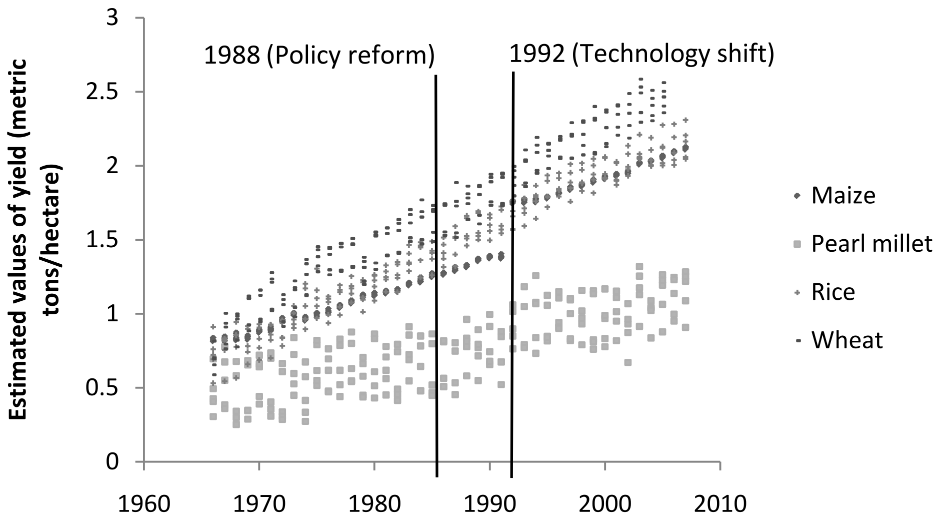
Variable	Model 1	Model 2	Model 3	Model 4
Dependent	Yield	Yield	Yield	Yield
Rainfall (millimeters)	0.0003***	0.0003***	0.0003***	0.0003***
	(0.0001)	(0.0000)	(0.0001)	(0.0001)
Real farm harvest price($t-1$) (INR/ton)	0.0005	0.0007	0.0002	0.0004
	(0.0019)	(0.0019)	(0.0018)	(0.0018)
Year of harvest (year)	0.0457***	0.0415***	0.0428***	0.0387***
	(0.0065)	(0.0085)	(0.0068)	(0.0089)
Percentage of crop area under high-yield varieties (%)	0.0019		0.0025	
	(0.0022)		(0.0023)	
Percentage of crop area under irrigation (%)		0.0069		0.0075
		(0.006)		(0.0065)
Real fertilizer price (INR/metric ton)	0.0024***	0.0024**	0.0024**	0.0025**
	(0.0011)	(0.0011)	(0.0011)	(0.0011)
Policy change (lagged)	0.0256	0.0099	0.0628	0.0531
	(0.0888)	(0.0870)	(0.0867)	(0.0857)
Constant	-89.7823**	-81.8389***	-84.1177***	-76.2333***
	(12.9179)	(16.5645)	(13.4622)	(17.4128)
Number of observations	200	205	200	205
Policy change lag (years)	4	4	6	6
Estimation	FGLS	FGLS	FGLS	FGLS

Source: Authors.
Note: Values in parentheses are standard errors. Coefficients are significant at the * 10 percent, ** 5 percent, and *** 1 percent levels, respectively.

Figure 3 provides a more visual representation of the structural changes in yield trends that have occurred since the introduction of policy reforms in 1988.[16] In this figure, the structural change in yields is most apparent in the shifts for pearl millet and maize. However, no such shift is observed for rice and wheat.

[16] Because of more or less similar results using different models, only the figure based on model 1 is presented.

Figure 3. Estimated values of yield based on model 1 for maize, pearl millet, rice, and wheat, 1966-2007, India



Source: Authors.

To generate further evidence from the models above, we also generate estimates from the pooled data for all crops using dummy variables for both states and crops, crop-year interaction terms, and crop-policy shift interaction terms. Estimation results are presented in Table A.5 and Table A.6 in the appendix. The coefficient for the interaction term between policy change and the crop dummy variable is positive and significant for maize and pearl millet suggesting that there was a structural change in the maize and pearl millet yield trends since reforms of 1988. However, this same interaction term is not statistically significant for rice, suggesting that there was no such structural change in the yield trends for rice since policy reforms of 1988. The more or less similar results from the pooled ordinary least square estimation further supports the findings from the crop-specific estimations that, because of the increased appropriability of hybrid crops, policy reforms had a positive and statistically significant effect on yield trends of maize and pearl millet, while there was no such effect for the self-pollinated crops, rice and wheat.

In sum, even though rice and wheat are grown under more favorable production conditions (that is, mainly in irrigated areas), policy reforms of the late 1980s in India did not result in any significant structural change in yield trends for these crops compared with the structural changes observed for maize and pearl millet. Because we control for factors such as farm harvest prices and fertilizer prices which could influence farmers' variable input use and thus yields, alternative explanations such as changes in commodity prices or input prices influencing these structural changes observed for maize and pearl millet are not supported. Since hybridization is the key difference between the two sets of crops, findings from this analysis suggest that the combination of policy reforms and technological change (in the form of hybridization, which proxies for enforceable IPRs) provided sufficient incentives for private R&D investment that was decidedly productivity enhancing.

6. POLICY IMPLICATIONS

By comparing and contrasting the results of yield trends for hybrid crops (maize and pearl millet) with those of self-pollinated crops (rice and wheat) in India, this study suggests the following. First, positive and statistically significant structural changes in the yield trends of hybrid crops occurred following the introduction of policy reforms in 1988. Second, no such changes in yield trends occurred for self-pollinated crops.

Although alternative explanations may exist, these findings suggest that the combination of supportive policy changes and enforceable (biological) IPRs encouraged greater private investment in maize and pearl millet improvement, ultimately leading to increases in yield growth rates. The statistical evidence pointing to structural changes in yield trends—when viewed alongside the well-documented historical evidence on changes in the public and private sectors' roles in crop-specific research, development, and delivery—suggests that India has leveraged both public science and private investment to accelerate productivity growth with respect to these two crops. In sum, the continuous yield gains generated by long-term public investment in research, policy reforms that encouraged private investment, and IPR protections conferred by maize and pearl millet hybrids represent a successful moment in Indian agriculture.

Despite this success, policymakers and analysts sometimes overlook or downplay the need for incentives created by public policy to stimulate private investment in crop research, development, and delivery. This has several implications for policy decisions, policy execution, and corporate strategies in India, all of which could otherwise influence India's long-term agricultural productivity growth and food security. We consider several such implications in the subsections that follow.

Results from this analysis imply that efforts to leverage the private sector as a means of revitalizing growth rates of rice and wheat yields may depend significantly on the introduction of some form of IPR protection (biological or legal) that encourages private investment. But there remains deep-rooted concern over the ability of well-designed policies to encourage the development of proprietary technologies that can generate new yield gains in Indian agriculture.

Potential of Private Hybrids

The private sector is well versed on the successful introduction of private hybrids of maize and pearl millet in India. Hybrids provided private firms with a way to appropriate the gains from innovation, and in the absence of sufficient legal IPR mechanisms, private firms will likely continue to invest in developing hybrids and conferring new traits on hybrids. This has already been demonstrated with the rapid diffusion of private cotton hybrids and, later, private genetically modified (GM) cotton hybrids conferred with the insect-resistant trait.[17]

To be sure, agricultural biotechnology has opened up new areas of potential in the Indian seed market. Private firms have managed to commercialize insect-resistant (*Bacillus thuringiensis* [Bt]) cotton, generating impressive impacts in India's cotton sector. As of 2008, Bt cotton was cultivated on more than 80 percent (approximately 7.6 million hectares) of India's cotton area by an estimated 5 million smallholders, and it has contributed to pesticide use reductions of 42 percent, yield increases of 30 percent, and increases in profits by 47 percent, transforming India from the world's third largest cotton importer in 2002–2003 to its second largest exporter in 2007–2008 (Sadashivappa and Qaim 2009; James 2008; Gruère, Mehta-Bhatt, and Sengupta 2008).

[17] Interestingly, it is the combination of good hybrids and good GM traits that has catapulted Nuziveedu Seeds into position as India's largest seller of Bacillus thuringiensis (Bt) cotton seed. The hybrids were developed by Nuziveedu Seeds, whereas the Bt trait is licensed from Mahyco Monsanto Biotech Ltd.

The Continued Importance of Public R&D Investment

The appropriability offered by hybrids is not enough to encourage private investment in all crops. Other incentive mechanisms—other push and pull factors—are necessary. This includes public investment in upstream science and technology.

A fitting example here may be hybrid rice. Even though hybrid rice has the potential to accelerate India's sluggish yield growth in rice, other factors are confounding its uptake, including high levels of yield variability and poor grain and cooking qualities (see, for example, Ramasamy et al. 2003 and Janaiah 2002). This may suggest the need for public investment in more upstream research on hybrids, even despite concerns that the inherently commercial value of hybrids should militate against the use of public funding for research and development.

Possibilities of an Innovation Act for India

There is a need for more effective mechanisms to encourage the commercialization of public research in India. This suggests the need for reforms in how public research materials make their way into private breeding programs. Despite the large public stocks of germplasm and parental lines in research organizations and universities, the mechanisms with which to transfer and exchange materials, whether on an exclusive or nonexclusive basis, are still wanting.

One step in the right direction could be the promulgation of an act similar to the Bayh-Dole Act (Unnikrishnan 2010). The Bayh-Dole Act, introduced in the United States in 1980, allows public research organizations and universities to acquire patents over inventions that result from publicly funded research, and provides incentives for the inventors or their organizations (for example, remuneration on the order of 30 percent of any royalties earned from commercial licensing) to promote further innovation. The Indian adaptation—the proposed "Protection and Utilization of Publicly Funded Intellectual Property Bill, 2008," or the Innovation Bill—would similarly 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 (DST 2008). Although the exact provisions of the proposed legislation are still under discussion, the Innovation Bill could be one mechanism that would more fully integrate public research into India's burgeoning agricultural innovation system.

Need for an Enforceable *Legal* IPR Regime

Neither public R&D investment nor commercialization of private hybrids is sufficient to encourage greater private investment in India's seed industry. Although hybrids provide a firm with protection against farmers reusing the seed (and thus forgoing remuneration to the firm for its investment in R&D), they are fairly ineffective in preventing other firms from stealing its research. Thus, the need for an enforceable legal IPR regime remains, particularly if private firms are to protect themselves from the competition, diversify into lucrative crops and markets, and invest beyond hybrids.

Current developments in India show some positive sign of progress on this front. The large number of applications from the private sector for PVP certificates for novel varieties in India suggests that industry is responding positively to the 2001 PPV&FR Act. But the ability of the courts to adjudicate infringement cases in a speedy manner, and to ensure the protection of those who have had their IPRs violated by infringements, remains to be tested.

When PVP certification is combined with effective implementation of the 2002 National Seeds Policy and the (still pending) 2004 Seed Bill, both firms and farmers stand to gain. Firms will have a much greater incentive to innovate as a result of the strong combination of legal IPRs, mandatory registration of varieties, and registration of seed producers and dealers. This combination can also protect farmers from spurious seed, predatory corporate practices, and other behaviors that exploit the inherent information asymmetries between farmers and seed sellers.

7. CONCLUSIONS

Cereal output and yield growth in India have slowed in recent years, with annual yield growth falling below 1 percent in recent years and remaining well below annual population growth for more than a decade. Meanwhile, the gains of the Green Revolution are rapidly eroding for major cereals as annual yield growth during the period 1989–2008 was 31 percent and 61 percent lower than the yield growth during the period 1968–1988 for rice and wheat, respectively.

The evidence discussed in this paper demonstrates how maize and pearl millet yields have grown much more rapidly than yields of wheat and rice in recent decades due to (1) policies that encouraged private investment in the seed industry, (2) public hybrid breeding programs that generated new seeds offering substantial yield gains, and (3) biological IPRs conferred by hybridization that conveniently married the private sector's need for appropriability with the nation's need for productivity growth. Although past lessons are not an indication of future success, this convergence of policy solutions and technology opportunities can be replicated for other crops that are vital to India's food security.
This replication strategy may be essential to India's long-term food security. A reversal of the slowing trend in rice and wheat yield growth will have to capitalize on long-term public investment in research, policy reforms that encourage private investment in agriculture, and a strong IPR regime that leverages both biological and legal forms of protection.

Indeed, there are signs that India is moving in the right direction, despite the vibrant discourse and public debates that may suggest otherwise. India has not only emerged as the regional leader in agricultural R&D, but has opened the door for private investment in the field with a fairly conducive policy regime. In response, private firms have entered the market quite readily since the mid-1980s, and have effectively managed the issue of appropriability by concentrating themselves in the market for hybrid seed. More recent policy reforms suggest even greater opportunities, including the introduction of a strong regime for legal IPRs and new technological opportunities afforded by agbiotech.

However, further policy solutions are needed. Continued public investment in agricultural R&D remains essential, even in the development of hybrids. New incentives such as an innovation act are needed to encourage the commercialization of public research. And the enforcement of legal IPRs through the adjudication of infringement cases needs to be pursued to create the necessary precedents and incentives for private-sector support in the 2001 PPV&FR Act.

In conclusion, India has demonstrated that the private sector can contribute to improving agricultural productivity and food security through the research, development, and delivery of pearl millet and maize hybrids. A more conducive policy environment and an expanding technological frontier suggest that private-sector innovation can contribute even more.

APPENDIX: SUPPLEMENTARY TABLES

A.1. Estimation results of seemingly unrelated regression of maize yield, 1966–2007

Variable	Andhra Pradesh	Uttar Pradesh	Bihar	Madhya Pradesh	Rajasthan
Dependent	Yield	Yield	Yield	Yield	Yield
Rainfall (millimeters)	0.0003	-0.0004	-0.0003*	0.0002	0.0008***
	(0.0003)	(0.0002)	(0.0002)	(0.0002)	(0.0003)
Real farm harvest price(t – 1) (INR/metric ton)	0.0246**	0.0021	0.0103**	0.0065	0.0044
	(0.0099)	(0.0042)	(0.0047)	(0.0065)	(0.0056)
Year of harvest (year)	0.0948***	-0.0043	0.0319**	0.0097	0.0379**
	(0.0233)	(0.0134)	(0.0129)	(0.0147)	(0.0165)
Percentage of area under high-yield varieties (%)	-0.0131	0.0084	0.0000	0.0098	-0.0148
	(0.0125)	(0.0081)	(0.0077)	(0.0089)	(0.0099)
Real fertilizer price (INR/metric ton)	0.0037	-0.0035	-0.0037	0.0001	0.0003
	(0.0036)	(0.0022)	(0.0024)	(0.0028)	(0.0031)
Policy change (lagged)	0.4564**	0.0355	0.3661***	-0.0458	0.0302
	(0.1873)	(0.1178)	(0.1158)	(0.1454)	(0.1580)
Constant	-187.2072***	9.9728	-61.7961**	-18.8238	-74.2217**
	(46.0202)	(26.6241)	(25.6054)	(29.0198)	(32.6602)
Number of observations	42	42	42	42	42
R^2	0.90	0.67	0.89	0.55	0.37
Policy change lag (years)	6	6	6	6	6
Estimation	SUR	SUR	SUR	SUR	SUR

Source: Authors.
Note: Values in parentheses denote standard errors. SUR = seemingly unrelated regression. Coefficients are significant at the * 10 percent, ** 5 percent, and *** 1 percent levels, respectively.

A.2. Estimation results of seemingly unrelated regression of pearl millet yield, 1966–2007

Variable	Andhra Pradesh	Gujarat	Madhya Pradesh	Rajasthan	Uttar Pradesh
Dependent	Yield	Yield	Yield	Yield	Yield
Rainfall (millimeters)	0.0004***	0.0006***	0.0000	0.0005***	0.0001
	(0.0001)	(0.0001)	(0.0001)	(0.0002)	(0.0002)
Real farm harvest price ($t-1$) (INR/metric ton)	0.0003	-0.0061*	0.0055	0.0027	0.0033
	(0.0027)	(0.0033)	(0.0039)	(0.0032)	(0.0029)
Year of harvest (year)	0.0182**	0.0133	0.025*	0.0258*	0.0189*
	(0.0084)	(0.0137)	(0.0147)	(0.01349)	(0.0109)
Percentage of area under high-yield varieties (%)	-0.0079***	-0.0042	-0.0045	-0.0039	0.0025
	(0.0028)	(0.0050)	(0.0054)	(0.0052)	(0.0042)
Real fertilizer price (INR/metric ton)	-0.0017*	-0.008	-0.0010	0.0015	-0.0005
	(0.0010)	(0.0017)	(0.0019)	90.0017)	(0.0014)
Policy change (lagged)	0.1099*	0.0519	0.1753*	0.0091	0.0773
	(0.0562)	(0.0941)	(0.0999)	(0.0869)	(0.0783)
Constant	-35.2943**	-25.2828	-48.1116	-51.2409	-36.9760*
	(16.5809)	(27.1401)	(28.9825)	(26.6548)	(21.5351)
Number of observations	42	42	42	42	42
R^2	0.81	0.73	0.72	0.56	0.87
Policy change lag (years)	6	6	6	6	6
Estimation	SUR	SUR	SUR	SUR	SUR

Source: Authors.
Note: Values in parentheses denote standard errors. SUR = seemingly unrelated regression. Coefficients are significant at the * 10 percent, ** 5 percent, and *** 1 percent levels, respectively.

A.3. Estimation results of seemingly unrelated regression of rice yield, 1966–2007

Variable	Karnataka	Andhra Pradesh	Bihar	Uttar Pradesh	Assam
Dependent	Yield	Yield	Yield	Yield	Yield
Rainfall (millimeters)	0.0003	0.0003**	0.0004***	0.0009***	-0.0001*
	(0.0002)	(0.0001)	(0.0001)	(0.0002)	(0.0001)
Real farm harvest price (t − 1) (INR/metric ton)	-0.0051	-0.0019	0.0067*	0.0053	0.0041*
	(0.0067)	(0.0062)	(0.0038)	(0.0055)	(0.0023)
Year of harvest (year)	0.0301*	0.0475***	0.0006	0.0397***	0.0177***
	(0.0181)	(0.0102)	(0.0105)	(0.0109)	(0.0048)
Percentage of area under High yield varieties (%)	-0.0097	-0.0056	0.0079*	0.0039	-0.0021
	(0.0077)	(0.0040)	(0.0046)	(0.0053)	(0.0019)
Real fertilizer price (INR/metric ton)	-0.0017	-0.0019	-0.0003	-0.0009	-0.0005
	(0.0029)	(0.0062)	(0.0017)	(0.0016)	(0.0007)
Policy change (lagged)	0.1609	-0.1060	0.1551	-0.0353	0.0494
	(0.1631)	(0.0891)	(0.1036)	(0.0935)	(0.0473)
Constant	-57.2185	-91.6475***	-1.1744	-78.6101***	-33.7792***
	(35.6427)	(20.0988)	(20.8726)	(21.7263)	(9.4187)
Number of observations	42	42	42	42	42
R^2	0.69	0.95	0.70	0.94	0.90
Policy change lag (years)	6	6	6	6	6
Estimation	SUR	SUR	SUR	SUR	SUR

Source: Authors.
Note: Values in parentheses denote standard errors. SUR = seemingly unrelated regression. Coefficients are significant at the * 10 percent, ** 5 percent, and *** 1 percent levels, respectively.

A.4. Estimation results of seemingly unrelated regression of wheat yield, 1966–2007

Variable	Bihar	Uttar Pradesh	Madhya Pradesh	Rajasthan	**Haryana**
Dependent	Yield	Yield	Yield	Yield	Yield
Rainfall (millimeters)	0.0003*	0.0005***	0.0004***	0.0001	0.0003*
	(0.0002)	(0.0001)	(0.0001)	(0.0002)	(0.0002)
Real farm harvest price ($t-1$) (INR/metric ton)	0.0024	-0.0003	0.0034	0.0009	0.0010
	(0.0036)	(0.0022)	(0.0027)	(0.0043)	(0.0068)
Year of harvest (year)	0.0053	0.054***	0.0212***	0.0508***	0.0846***
	(0.0117)	(0.0069)	(0.0065)	(0.0107)	(0.0134)
Percentage of area under high yield varieties (%)	0.011***	-0.0017	0.0019	0.0004	-0.0041
	(0.0036)	(0.0021)	(0.0018)	(0.0035)	(0.0050)
Real fertilizer price (INR/metric ton)	-0.0003	-0.0001	-0.0025*	0.0003	-0.0003
	(0.0022)	(0.0013)	(0.0013)	(0.0019)	(0.0025)
Policy change (lagged)	0.2579*	-0.0328	0.0913	0.0466	-0.1847
	(0.1429)	(0.0823)	(0.0798)	(0.1292)	(0.1670)
Constant	-10.2911	-106.03***	-41.332***	-99.0844***	-164.9648***
	(23.2693)	(13.6478)	(12.9823)	(21.2346)	(26.6191)
Number of observations	40	40	40	40	40
R^2	0.78	0.96	0.93	0.92	0.94
Policy change lag (years)	6	6	6	6	6
Estimation	SUR	SUR	SUR	SUR	SUR

Source: Authors.
Note: Values in parentheses denote standard errors. SUR = seemingly unrelated regression. Coefficients are significant at the * 10 percent, ** 5 percent, and *** 1 percent levels, respectively.

A.5. Estimation results of pooled regression using maize, pearl millet, rice and wheat, 1966–2007

Variable	Coefficient	Coefficient
Model	Model 1	Model 2
Dependent	Log(yield)	Log(yield)
Rainfall (millimeters)	0.0003***(0.0001)	0.0003***(0.0001)
Real farm harvest price (*t* – 1) (INR/metric ton)	0.0046***(0.0016)	0.0039**(0.0016)
Year of harvest (year)	0.0309***(0.0060)	0.0386***(0.0077)
Percentage of area under high yield varieties (%)	0.0026(0.0018)	
Percentage of area under irrigation (%)		-0.0015(0.0049)
Real fertilizer price (INR/metric ton)	-0.0000(0.0008)	0.0001(0.0008)
Policy change (lagged)	18.6345**(8.1882)	25.6144***(7.3009)
Year*policy change	-0.0094**(0.0041)	-0.0129***(0.0037)
Pearl millet	25.3753**(9.7701)	27.7028*(14.8417)
Maize	21.2234**(9.1226)	27.9018*(14.9068)
Rice	22.3653***(7.7499)	21.8265**(10.1889)
Pearl millet*policy change	0.2269*(0.1185)	0.2867**(0.1200)
Maize*policy change	0.1893*(0.1032)	0.2608***(0.00993)
Rice*policy change	0.0813(0.0799)	0.1022(0.0833)
Year*maize	-0.0108**(0.0046)	-0.0143*(0.0076)
Year*pearl millet	-0.0133***(0.0049)	0-0.01446*(0.0076)
Year*rice	-0.01138***(0.0039)	-0.0112**(0.0051)
Andhra Pradesh	0.3797***(0.0431)	0.3712***(0.0427)
Madhya Pradesh	-0.1780***(0.0369)	-0.1784***(0.0369)
Bihar	-0.1864***(0.0336)	-0.1902***(0.0337)
Rajasthan	-0.2315***(0.0567)	-0.2347***(0.0564)
Gujarat	0.3508***(0.0567)	0.3517***(0.0591)
Karnataka	0.2756***(0.0439)	0.2793***(0.0444)
Assam	-0.3713***(0.0438)	-0.3835***(0.0444)
Haryana	0.5564***(0.0458)	0.5512***(0.0452)
Constant	-61.4872***(11.9523)	-76.2518***(14.9541)
Number of observations	830	830
R^2	0.77	0.77
Policy change lag (years)	4	4
Estimation	Pooled OLS	Pooled OLS

Source: Authors.
Note: Values in parentheses denote standard errors. Coefficients are significant at the * 10 percent, ** 5 percent, and *** 1 percent levels, respectively. For the crop dummy variable, wheat is used as the reference crop; for the state dummy variable, Uttar Pradesh is used as the reference state. For this estimation, a logarithmic transformation of dependent variable (yield) was used to address the issue of autocorrelation in the data.

A.6. Estimation results of pooled regression using maize, pearl millet, rice and wheat, 1966–2007

Variable	Coefficient	Coefficient
Model	Model 3	Model 4
Dependent	Log(yield)	Log(Yield)
Rainfall (millimeters)	0.0003***(0.0001)	0.0003***(0.0001)
Real farm harvest price ($t-1$) (INR/metric ton)	0.0051***(0.0015)	0.0044***(0.0015)
Year of harvest (year)	0.0309***(0.0058)	0.0396***(0.0082)
Percentage of area under high yield varieties (%)	0.0026(0.0018)	
Percentage of area under irrigation (%)		-0.0024(0.0054)
Real fertilizer price (INR/metric ton)	-0.0001(0.0008)	0.0000(0.0001)
Policy change (lagged)	19.5514**(7.9121)	26.1546***(7.0829)
Year*policy change	-0.0098**(0.0039)	-0.0132***(0.0036)
Pearl millet	19.4490**(8.9015)	25.1460(15.5352)
Maize	17.2284**(8.4193)	25.7611*(15.3282)
Rice	21.0037***(7.3372)	22.5530**(10.9179)
Pearl millet*policy change	0.1461(0.1178)	0.2347**(0.1186)
Maize*policy change	0.1345(0.1006)	0.2143**(0.0974)
Rice*policy change	0.0603(0.07781)	0.0994(0.0874)
Year*maize	-0.0088**(0.0043)	-0.0132*(0.0078)
Year*pearl millet	-0.0103**(0.0045)	-0.0133*(0.0079)
Year*rice	-0.0107***(0.0037)	-0.01154**(0.0056)
Andhra Pradesh	0.3801***(0.0435)	0.3712***(0.0430)
Madhya Pradesh	-0.1791***(0.0370)	-0.1793***(0.0369)
Bihar	-0.1886***(0.0335)	-0.1920***(0.0335)
Rajasthan	-0.1886***(0.0335)	-0.2365***(0.0564)
Gujarat	0.3463***(0.0601)	0.3475***(0.0593)
Karnataka	0.2709***(0.0439)	0.2756***(0.0445)
Assam	-0.3689***(0.0439)	-0.3829***(0.0445)
Haryana	0.5575***(0.0461)	0.5516***(0.0453)
Constant	61.5038***(11.5406)	-78.3400***(16.0783)
Number of observations	830	830
R^2	0.77	0.77
Policy change lag (years)	6	6
Estimation	Pooled OLS	Pooled OLS

Source: Authors.
Note: Values in parentheses denote standard errors. Coefficients are significant at the * 10 percent, ** 5 percent, and *** 1 percent levels, respectively. For the crop dummy variable, wheat is used as the reference crop; for the state dummy variable, Uttar Pradesh is used as the reference state. For this estimation, a logarithmic transformation of dependent variable (yield) was used to address the issue of autocorrelation in the data.

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