United States Department of Agriculture

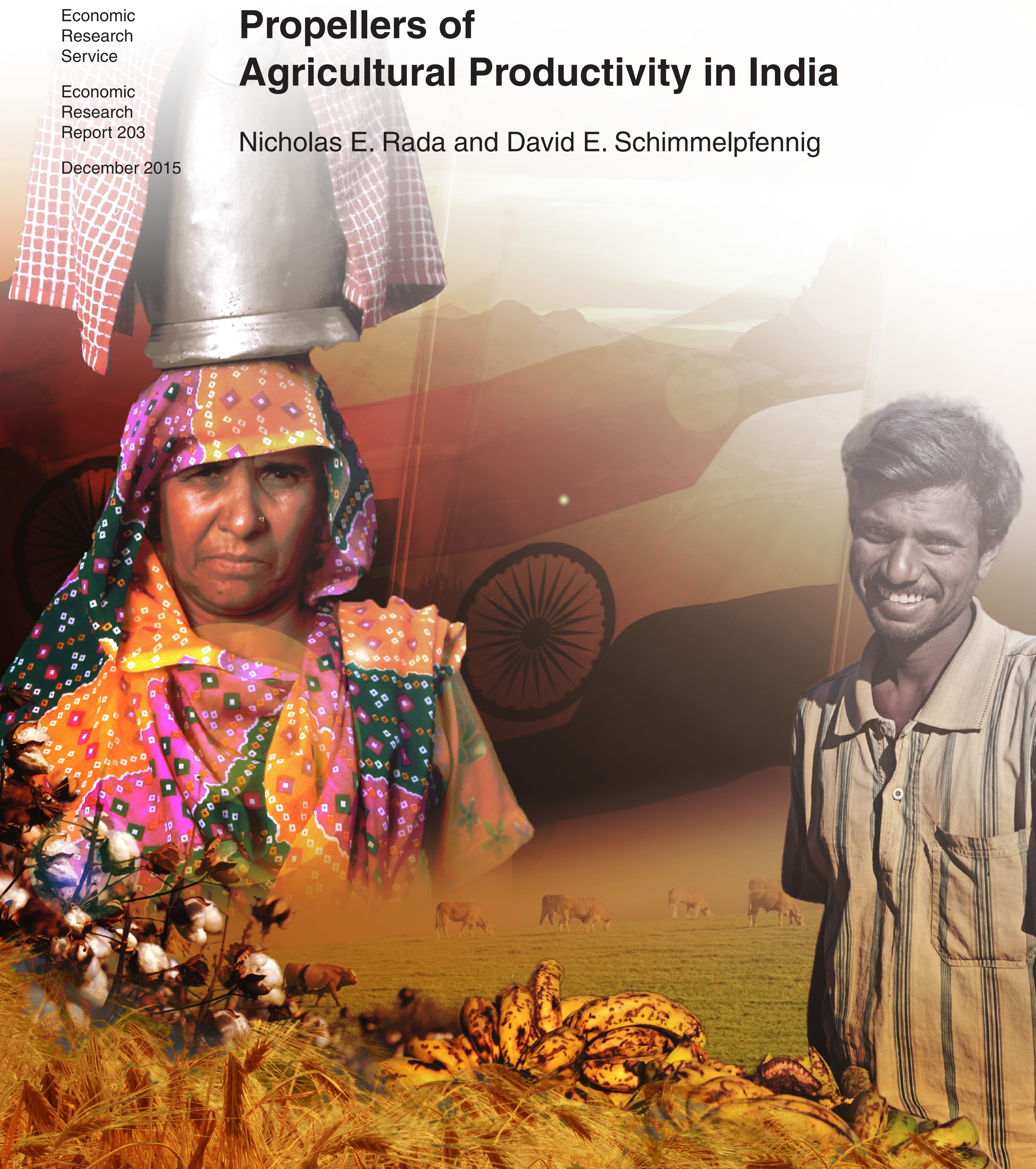
Economic
Research
Service

Economic
Research
Report 203

December 2015

Propellers of Agricultural Productivity in India

Nicholas E. Rada and David E. Schimmelpfennig



United States Department of Agriculture

Economic Research Service
www.ers.usda.gov

Access this report online:

www.ers.usda.gov/publications/err-economic-research-report/err203

Download the charts contained in this report:

- Go to the report's index page www.ers.usda.gov/publications/err-economic-research-report/err203
- Click on the bulleted item "Download err203.zip"
- Open the chart you want, then save it to your computer

Recommended citation format for this publication:

Nicholas E. Rada and David E. Schimmelpfennig. *Propellers of Agricultural Productivity in India*, ERR-203, U.S. Department of Agriculture, Economic Research Service, December 2015.

Cover is a derivative of images from iStock; design by Ethiene Salgado.

Use of commercial and trade names does not imply approval or constitute endorsement by USDA.

The U.S. Department of Agriculture (USDA) prohibits discrimination in all its programs and activities on the basis of race, color, national origin, age, disability, and, where applicable, sex, marital status, familial status, parental status, religion, sexual orientation, genetic information, political beliefs, reprisal, or because all or a part of an individual's income is derived from any public assistance program. (Not all prohibited bases apply to all programs.) Persons with disabilities who require alternative means for communication of program information (Braille, large print, audiotape, etc.) should contact USDA's TARGET Center at (202) 720-2600 (voice and TDD).

To file a complaint of discrimination write to USDA, Director, Office of Civil Rights, 1400 Independence Avenue, S.W., Washington, D.C. 20250-9410 or call (800) 795-3272 (voice) or (202) 720-6382 (TDD). USDA is an equal opportunity provider and employer.

United States Department of Agriculture

Economic Research Service

Economic
Research
Report 203

December 2015

Propellers of Agricultural Productivity in India

Nicholas E. Rada and David E. Schimmelpfennig

Abstract

India's decelerating wheat- and rice-yield growth rates have led to questions of whether India's agricultural sector will be able to meet future food demands. To explore this issue, ERS researchers measure sector-level agricultural total factor productivity (TFP) growth and evaluate how public policies affected TFP from 1980 to 2008. During this period, substantial regional differences in TFP growth emerged: the Indian West and South achieved faster TFP growth than the rest of the country, largely due to rapid growth in horticulture and animal products. Of the policies hypothesized to stimulate TFP, India's public agricultural research and higher education programs had the greatest effect on TFP growth, followed by public investments in irrigation infrastructure. These effects propelled TFP in Northern and Western India more than in the rest of the country. Groundwater irrigation from wells accelerated TFP more than surface-water irrigation from canals. Other drivers of TFP growth included research investments of international institutions and an emerging private sector. Public investment in rural education has had mixed effects, depending on education levels. These findings support an optimistic view that Indian agriculture will be able to meet the broadening spectrum of future food demands. Critical to that optimism, though, is continued innovation from public and private research systems, especially in seed development, and from irrigation and high-value-commodity production technologies.

Keywords: national agricultural research, returns to research, total factor productivity (TFP), CGIAR, international agricultural research, India, irrigation, education.

Acknowledgments

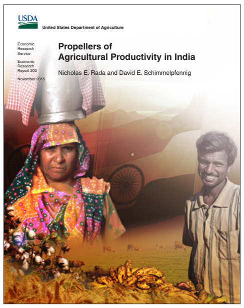
The authors thank Keith Fuglie, USDA, Economic Research Service (ERS); Madhur Gautum, World Bank; Suresh Pal, Indian Agricultural Research Institute; Rajesh Mehta, Research and Information System for Developing Countries; Ganesh Kumar Anand, Indira Gandhi Institute of Development Research; and Sanjay Kumar Prasad, PK Joshi, and Nirupam Datta, International Food Policy Research, for their insight, work, and guidance on this report. The authors thank the following people for their peer-review and comments: Rip Landes and Carlos Arnade, USDA, ERS; Spiro Stefano, University of Florida; Prabhu Pingali, Cornell University; and Levin Flake, USDA, Foreign

Agricultural Service. The authors also appreciate comments from participants at the International Food Policy Research Institute and Institute of Economic Growth co-sponsored conference *Innovation in Indian Agriculture*: *Ways Forward* in New Delhi, India, 2014. Thanks also to editor Maria Williams and designer Ethiene Salgado-Rodriguez, USDA, ERS.

Contents

United States Department of Agriculture

A report summary from the Economic Research Service December 2015



United States Department of Agriculture

Economic
Research
Service

Economic
Research
Report 203

November 2015

Propellers of
Agricultural Productivity in India

Nicholas E. Rada and David E. Schimmelpfennig

Find the full report at *www.ers.usda.gov/publications/err-economic-research-report/err203*

Propellers of Agricultural Productivity in India

Nicholas E. Rada and David E. Schimmelpfennig

What Is the Issue?

In recent years, economists have questioned India's continued ability to supply food to its 1.24 billion citizens. Central to these questions has been the waning impact of cereal grain technologies typified by the Green Revolution, concurrent with rising consumer demand for high-value foods. Key determinants of India's food supply and income growth are the rate of agricultural productivity growth and how its major sources affect that growth. Because India's regions differ substantially in the quality and quantity of their natural resources and levels of average income, a regional evaluation of productivity growth is critical to understanding the policies propelling growth.

What Did the Study Find?

Between 1980 and 2008, India's agricultural growth has expanded beyond the Northern grain belt, led primarily by rapid production growth in horticulture and livestock products. India's agricultural output grew, on average, by 3.1 percent per year. That growth was due more to an increase in productivity than to an increase in resources; efficiency and technical changes accounted for 66 percent of that growth, while more conventional inputs (land, labor, capital, and materials) accounted for 34 percent. Over the same period, Indian agriculture's productivity growth rate averaged 2.1 percent per year. However, productivity growth rates varied considerably by region: the Center (1.7 percent) and Northeast (1.0 percent) regions showed the slowest growth; the North (1.9 percent) and East (1.9 percent) regions showed faster growth; and the West (2.3 percent) and South (2.7 percent) regions showed the fastest growth.

ERS researchers identified several policies propelling productivity growth in Indian agriculture. Of these, public investments in both India's agricultural research and higher education system and its irrigation infrastructure had the greatest effects on productivity. From 1980 to 2008, public investment in agricultural research had the greatest effect on productivity in the northern, western, and central States. India's average return on public investment in its agricultural research and higher education system was 85 percent: for each $1 invested in India's research-and-education program, $18.34 in research benefits were generated.

The second-greatest effect on productivity was from an expansion of irrigated area. During the 1980-2008 period, extending irrigation infrastructure had a greater effect on productivity in the northern and western States than in the rest of the country. Focusing on the sources of irrigation, India's expansion of groundwater-well-irrigated area had a larger effect on productivity growth than did the expansion of canal-irrigated area. Groundwater wells have released the geographic constraint presented by accessing canal water, which in turn has boosted production by allowing more land to be double cropped. Investments in public rural education had mixed productivity effects. Investments in education accelerated productivity when the per capita average level of rural schooling was already greater than 4.3 years. However, when the average level of education was less than 4.3 years, the investments dampened productivity growth. Reaching 4.3 years of education is thus important for farm labor to successfully adapt and adopt new farm technologies and practices, thereby improving productive efficiency. International public agricultural research investments also contributed to India's rising productivity growth, although the effects were difficult to disentangle from those of private research investments.

How Was the Study Conducted?

To evaluate agricultural sector productivity change from 1980 to 2008, ERS researchers constructed output, input, and total factor productivity (TFP) quantity indexes for each Indian State as well as at the regional and national levels. TFP growth is defined as the difference between agricultural output growth and the weighted sum of land, labor, capital, and materials applied in the sector. Each input's aggregation weight is obtained from its relative share of total expenditures; each output's aggregation weight is obtained from its relative share of total revenues. A comprehensive State-level dataset was assembled, accounting for a broader mix of outputs than previous studies to more fully capture the agricultural sector's growth from 1980 to 2008, the last year for which State-level data were available. ERS researchers investigated the effects of India's research and development on TFP, including examination of how national research benefits were modeled.

Propellers of Agricultural Productivity in India

Introduction

The Green Revolution in India was an agricultural strategy to achieve grain self-sufficiency following severe droughts in 1965-66 and 1966-67. The Indian Government restructured its agricultural research and extension services to facilitate rapid farmer adoption of high-yielding, fertilizer-responsive, semi-dwarf wheat and rice varieties developed by international agricultural research systems. The country concurrently invested heavily in irrigation, transportation, and marketplace infrastructure—as well as in price supports to intensify grain production, particularly in the Indian North (Sims, 1993; Evenson et al., 1999). These strategies continue to shape Indian agricultural policy in the forms of heavily regionalized and commodity-specific input subsidies, output price supports, and Government procurement programs (Shreedhar et al., 2012).

Yet India has experienced substantial change since the 1960s. Economic growth over the past 45 years has boosted incomes; gross domestic product (GDP) per capita (in 2005-constant U.S. dollars) has grown from $267 in 1969-71 to $1,169 in 2011-13 (ERS, 2014). As incomes rose, consumer food demand expanded to include higher valued foods, such as fruit, vegetables, and some meat products. Indian farmers appear to be meeting these new growth opportunities. Agricultural GDP growth (2005 U.S.$) rose from an average annual rate of 1.5 percent in the 1960s to 3.3 percent in the 2000-2012 period (World Bank, 2014a), a reflection of the sector's transition beyond primary grain specialization. The rise in high-value production occurred simultaneously with consistent decreases in, since the 1980s, the share of area planted to primary food grains (Singh and Pal, 2010). Evidence from the literature suggests that farmers' decisions to allocate land to higher valued outputs accounted for roughly 30 percent of aggregate crop output growth between the early 1980s and the late 2000s (Rada, 2013; Birthal et al., 2008).

As India's farmers diversify their output mix, concerns have arisen about the agricultural sector's ability to meet the food needs of India's 1.24 billion citizens. India's new food security plan anticipates supplying up to 5 kilograms of food grain per month at subsidized prices to roughly two-thirds of its population. A fundamental concern for meeting new grain demands has been the long-term decelerating growth rate of rice and wheat total factor productivity (TFP)[1] (Chand et al., 2011). Further, boosting the availability of high-value foods for India's new burgeoning middle-class will require substantial new investment in transportation and market infrastructure and post-harvest technologies (Pingali, 2006).

This study assesses India's agricultural performance post-Green Revolution—a period capturing its recent agricultural diversification to high-value outputs. Using a growth accounting framework on a more complete set of agricultural outputs than past studies have used, we measure sectoral TFP growth since 1980 and evaluate how India's agricultural policies have affected that growth. Specifically, we examine the TFP-growth impact of public investments in national and international agricultural research, of irrigation infrastructure, and of public investments in transportation infrastructure and human capital development. We further control for rainfall variations and other trending factors that may be propelling India's farm TFP, such as private agricultural research investments.

---

[1] Total factor productivity is a ratio of total output to total conventional inputs employed in production.

A Review of Agricultural Research in India

Agricultural research's critical role in boosting India's farm productivity has been well documented (Easter et al., l977; Rosegrant and Evenson, 1992; Fan et al., 1999; Joshi et al., 2005; Chand et al., 2011). India's investments in agricultural research have produced significant returns: Pal and Byerlee (2006) reviewed 28 studies of India's internal rate of return to research investment and found an average return of 71.8 percent and a median return of 57.5 percent. With such high returns, it is of little surprise that as of 2008, India's investments in its agricultural research system ranked fourth globally (behind the United States, Japan, and China) and second among developing countries (Beintema et al., 2008).[2]

India's present public agricultural research system is based on the university land-grant system pioneered by the United States. In the Indian system, public research spending also includes investments in higher education. India's two-tiered research system is made up of the Indian Council for Agricultural Research (ICAR) at the Federal level and State Agricultural Universities (SAUs) at the State level. The ICAR-SAU research system accounted for 93 percent of total public research expenditures in 2003, falling to 88 percent in 2009 (Beintema et al., 2008; Pal et al., 2012). That 2009 estimate declines to 71 percent if private research is included (Pal et al., 2012).

ICAR, originally established in 1929, is a semiautonomous body that supports and coordinates agricultural research over a national scope. ICAR funds and manages 5 national institutes for basic and strategic research and postgraduate education; 42 central research institutes for commodity-specific research; 4 national bureaus for conservation and germplasm exchange and soil-survey work; 10 project directorates; 28 national research centers (NRCs) focusing on applied, commodity-specific, multidisciplinary strategic research of national importance (i.e., "mission mode" research focusing on farm technologies of national importance); and 82 All India Coordinated Research Projects (AICRPs) to promote multidisciplinary and multi-institutional research (Pal and Byerlee, 2006).

ICAR research spending shares by commodity show that in 2003, 50 percent of total expenditures were directed toward crops, which break down as follows: 8 percent to fruits and vegetables; 14 percent to rice, pulses, wheat, and sugarcane; and 27 percent to other crops (Beintema et al., 2008). Other notable shares include livestock (16 percent) and post-harvest technologies (10 percent). ICAR research capacity has also been directed primarily to crops; in 2009, roughly 40 percent of total full-time equivalent (FTE) scientists conducted crop research, and 20 percent conducted livestock research (Pal et al., 2012).[3]

SAUs conduct adaptive and applied research and higher education. Research spending at these institutions in 2003 was also directed primarily at crops: fruits and vegetables (11 percent); rice, pulses, wheat, and sugarcane (26 percent); and other crops (36 percent) (Beintema et al., 2008). Livestock research accounts for 13 percent of total public SAU research expenditures.

The number of SAUs has grown rapidly, from 31 in 2005 (Pal and Byerlee, 2006) to 55 in 2012 (Pal et al., 2012), to 70 in 2014 (Pal, 2014). The proliferation of SAUs reflects administrative reor-

---

[2] For comparison, spending is measured in international dollars (purchasing power parity dollars (PPP$)).

[3] In 1996-98, the share of FTE scientists conducting horticultural research was less than 5 percent of total ICAR research staff, and they received between 10 percent and 15 percent of total research expenditures (Pal and Byerlee, 2006). These data are not updated by Pal et al. (2012).

ganization (e.g., splitting existing SAUs and upgrading large campuses to university status) to raise the profile of research in such areas as animal science, horticulture, and fisheries. There has not, however, been a commensurate increase in FTE scientists or funding. In fact, between 2000 and 2009, the total number of FTE scientists working in the SAU system dropped by 20.8 percent, from 7,780 to 6,158 (Pal et al., 2012).

Functioning at the district (sub-State) level are 261 Krishi Vigyan Kendras (KVKs), or agricultural science centers. These centers, which are often dubbed “frontline extension” efforts, are funded by ICAR but are often under the administrative control of the SAUs. They function as experiment stations for field-level technology demonstration and local technology transfer (Pal et al., 2012; Pal and Byerlee, 2006).

In theory, the SAU focus is on applied adaptive research for local conditions, whereas ICAR leads overarching strategic and applied research. But in practice, their respective roles have blurred (Pal and Byerlee, 2006). Research may thus be conducted at ICAR or at an SAU, gains from research spillovers are coordinated by AICRPs, and the technologies may be demonstrated to local farmers through KVKs. India’s agricultural research system thus contains mechanisms for boosting human capital (through higher education and agricultural training), conducting applied research over a national scope in collaboration and coordination with local adaptive and maintenance research efforts, transferring research spillovers across States and commodities, and to some extent, disseminating new technologies to farmers through field-level demonstrations.

International Public Agricultural Research

The CGIAR (formerly, the Consultative Group for International Agricultural Research) was formally established in 1971, although individual research institutes conducted commodity-specific scientific research before then. Highlighted here are contributions to India’s wheat, rice, maize, and coarse grain production by the international agricultural research centers.

The International Maize and Wheat Improvement Center (CIMMYT) first developed wheat varieties for general cultivation in 1965. At the time, the role of Indian breeders was to conduct field tests for verifying high yields under Indian agronomic and climate conditions, and for consumer preferences (Evenson et al., 1999). Between 1990 and 2010, CIMMYT increased threefold the number of experimental wheat collections shared with India (CIMMYT, 2010). Exploiting the multi-institutional reach of India’s AICRP for Wheat, CIMMYT introduced 683 lines between 2006 and 2010 for acclimatization, evaluation, and release in India (CIMMYT, 2010).

The International Rice Research Institute (IRRI), established in 1960, made a major breakthrough in rice varietal research when it developed IR-8, the first semi-dwarf, high-yielding variety. IR-8 varieties were the focus of early Indian releases in the 1965-70 period because of their ability to focus energy into grain creation and a short stalk that didn’t collapse under its own weight when fertilizer was applied (Evenson et al., 1999). As Indian consumer preferences have changed, so too have the traits breeders incorporated in new varieties. For example, Pal et al. (2005) note that, between 1971 and 1980, 127 new rice varieties were developed; between 1981 and 1990, 223 new rice varieties were developed; and between 1991 and 2000, 257 new rice varieties were developed. While there has long been a focus on short- to medium-duration varieties (50 percent flowering in less than 100 days) and disease-resistant varieties, consumer preferences for long, slender fine-grain types of rice have led to increases in these varieties, rising from 29.1 percent in the 1971-1980 period to 36.5 percent in the 1991-2000 period.

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), established in 1972, has a mandate to conduct research on coarse grains, such as chickpeas, pigeon peas, groundnuts, pearl millet, sorghum, and other small millets, such as finger millet, little millet, and kodo millet. In the 1980s, ICRISAT developed the first open-pollinated varieties and hybrids of pearl millet (Evenson et al., 1999). New varieties of pearl millet and sorghum have been most readily employed by private researchers in India. Indeed, Evenson et al. (1999) show that private seed sales of both pearl millet and sorghum extensively employ ICRISAT and ICAR/SAU germplasm. It is worth noting that the ICAR/SAU contributions were developed from the millet and sorghum AICRPs.

Private Agricultural Research

Private companies in India over the 2008-09 period invested over $88 million (2005 U.S.$) in seed research (Pray and Nagarajan, 2013). This investment was more than double that devoted to either of the next two largest research areas, pesticides ($36 million) and agricultural machinery ($41 million) (Pray and Nagarajan, 2014). Multinationals invested less than half ($39 million) of total private seed research targeted to Indian agriculture in 2008-09; Indian seed companies accounted for the remainder ($49 million) (Pray and Nagarajan, 2014). The largest of such companies include Nuziveedu, Rasi, Ajeet, Ankur, Kaveri, and Namdhari Seed. Rallis India is a large seed breeding company that was acquired by Tata Chemicals in 2009 and also supplies chemical and fertilizer products. Private seed companies have made substantial investments in research spending, with total private seed research rising from $1.3 million in 1984-85 (2005 U.S.$), to $4.9 million in 1994-95, to $88.6 million in 2008-09.

Private research for pesticides and machinery also grew, though not at the pace achieved by the seed subsector. Pesticide research spending grew from $9 million in 1984-85, to $17 million in 1994-95 (Pray and Fuglie, 2001), to over $24 million in 2008-09 (Pray and Nagarajan, 2014). Machinery research grew from $3.7 million in 1984-85, to $6.5 million in 1994-95 (Pray and Fuglie, 2001), to over $40 million in 2008-09 (Pray and Nararajan, 2014).

The story of cotton and rice seed technologies in India highlights the key role of private research conducted abroad and brought to India in concert with the Indian regulatory system and public research institutions. In 1993, Monsanto partnered with Mahyco Seeds—an Indian multinational company—to bring Bacillus thuringiensis (Bt) cotton to India at the same time the technology was going through the approval process in the United States. After reviewing field trial data from the United States, the Indian Department of Biotechnology required Monsanto and Mahyco Seeds to form a joint venture (JV) in 1998 before giving permission to field test Bt cotton in India. After Bt cotton was introduced in the United States and China in 1996, the JV received limited approval for commercial agricultural use in 2001. When it became apparent that Bt seeds were being pirated and planted in nonapproved areas, the seeds were released nationwide in 2002.

In the case of rice, according to Ward et al. (2014), the most common drought-tolerant rice varieties were developed from public improvement of inbred lines later used primarily by resource-poor farmers; less common were varieties developed by the multinationals and seed companies as hybrids from public inbred lines that may yield up to 30 percent more under irrigation. Thus, the building blocks for rice varietal improvements often come from public research institutions. For example, the Indian private seed company Ajeet Seeds Ltd. is known for producing and marketing hybrids developed from public inbred lines (Bloomberg, 2015).

Measuring India's Agricultural Productivity

As noted earlier, concern has been raised over India's diminishing wheat and rice TFP growth rates. Chand et al. (2011) find average annual TFP growth of Indian wheat declined from 0.7 percent from 1986 to 1995 to 0.4 percent from 1996 to 2005, while rice TFP growth fell from 2.5 percent to 1.6 percent in the corresponding periods. But evaluating agricultural performance from commodity-specific TFP measures, while indicative of technical change with respect to a given crop, omits potential sources of growth that occur through diversifying farm output mix. Commodity TFP estimates therefore offer limited insight into sectoral TFP-growth improvements.

In this present report, TFP is measured using the chain-weighted Tornqvist-Theil quantity index. Thus, TFP growth is the difference between aggregate output growth and aggregate input growth. Aggregate output growth is defined as the sum of all commodity output growth rates, each growth rate weighted by its respective average revenue share in the reference time periods. Aggregate input growth is defined as the sum of all factor-input growth rates, each growth rate weighted by its respective average cost share in the reference time periods. (For technical details on how outputs and inputs are measured, see the "Technical Appendix.")

Our examination of India's farm productivity growth includes the broadest composition of commodities to date among studies using national accounts information (table 1). Specifically, we examine 59 crops and 4 livestock products across 16 Indian States, 6 regions, and at the national level (fig. 1). For the purposes of data consistency, Bihar is grouped with Jharkhand to form Old Bihar, Madhya Pradesh with Chhattisgarh to form Old Madhya Pradesh (Old MP), and Uttar Pradesh with Uttaranchal to form Old Uttar Pradesh (Old UP). These pairings into "Old" States reflect the former configurations, before the States were split in the year 2000.

Table 1

Agricultural crops and livestock products

Grain crops	Rice, maize, wheat, sorghum (jowar), pearl millet (bajra), finger millet (ragi), and barley
Pulse crops	Pigeon pea (arhar), chick pea (gram), urad (black gram), moong (green gram), kultha (horse gram), and lentils (masoor)
Horticulture crops	Dry peas, potatoes, tomatoes, onions, cabbages, cauliflower, green peas, sweet potatoes, tapioca, cashew nuts, bananas, pineapples, mangoes and guavas, oranges (including mandarins and mousambis), lemons, grapes, melons, papayas, apples, pears and quince, coffee, tea, cardamom, coriander, ginger, tumeric, chilies, garlic, and arecanuts
Oilseed crops	Soybeans, groundnuts, linseed, sunflower seed, castor, nigerseed, safflower, and sesamum
Specialty crops	Natural rubber, coconuts, cotton, jute, mesta, sannhemp, sugarcane, tobacco, and guarseed
Animal products	Wool, eggs, milk, and meat

Notes: Names of grain and pulse crops in parentheses are the Indian names.
Source: See Appendix table 1.

Figure 1

Regions and States of India

Note: For the purposes of data consistency, Jharkhand is combined with Bihar to form Old Bihar, Madhya Pradesh with Chhattisgarh to form Old Madhya Pradesh, and Uttar Pradesh with Uttaranchal to form Old Uttar Pradesh. These pairings into “Old” States reflect the former configurations, before the States were split in the year 2000.
Source: USDA, Economic Research Service.

Production Data

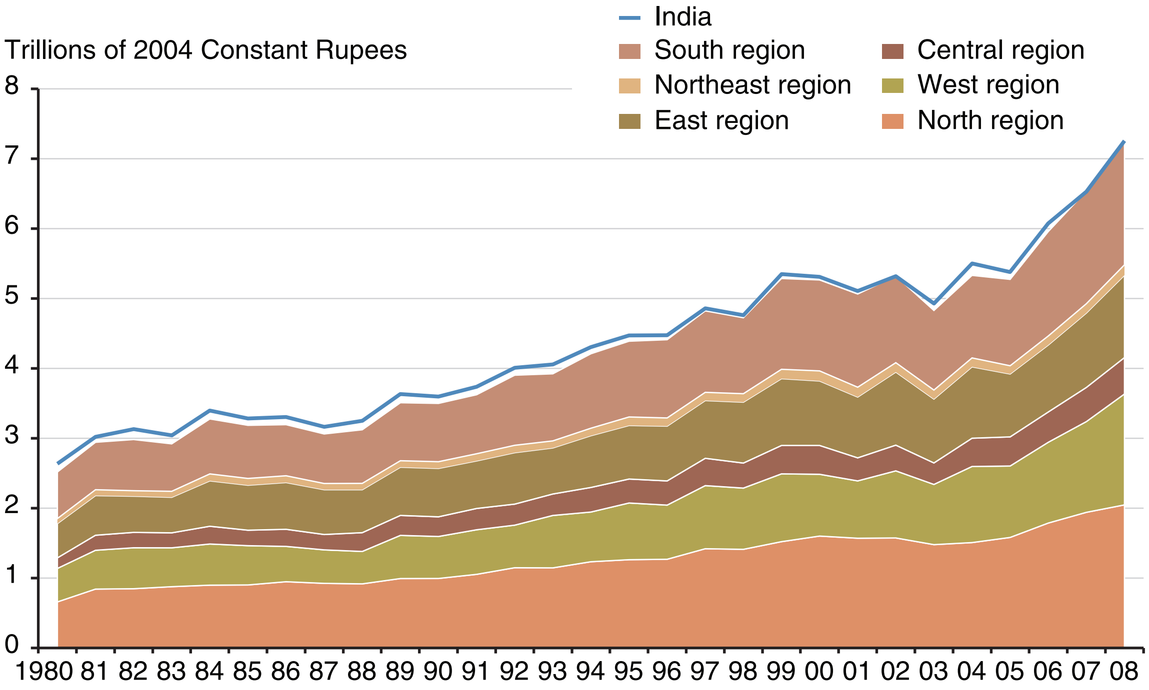
The 16 Indian States included in the analysis accounted for 98 percent of India's national agricultural production value, as averaged over the 1980-2008 period. India's real value of farm production increased an average 3 percent each year, rising from 2.6 trillion rupees to 7.3 trillion rupees, or from $42 billion to $116 billion (fig. 2).[4] The Indian West experienced the greatest average annual growth rate of 3.5 percent, followed closely by the South's and North's equal growth rates of 3.2 percent.

India's substantial growth in agricultural production value, however, was not equal across Indian States (fig. 3). Haryana (4.1 percent), Andhra Pradesh (4.0 percent), and Punjab (4.0 percent) had India's most rapid annual average value growth. Other States, such as West Bengal (3.7 percent), Himachal Pradesh and Rajasthan (3.6 percent), Gujarat (3.5 percent), and Maharashtra (3.4 percent) also achieved relatively high growth. The lowest average annual value of production growth rates were in Old Bihar (1.7 percent) and Orissa (1.8 percent).

We construct production quantity growth indexes to evaluate which commodity groups had the most accelerated volume growth. A look at average production shares in the 1980-84 and the 2004-08 periods shows that growth in production of animal and horticulture products reduced the share of production growth attributable to grains (fig. 4). When the production growth shares are viewed regionally, they show Indian regions specializing in commodity production (fig. 5). For instance, the Indian North was unique in its specialization in grain production. National oilseed production growth moved little over the 1980-84 and 2004-08 periods because Central India compensated

Figure 2

Increasing total value of agricultural production



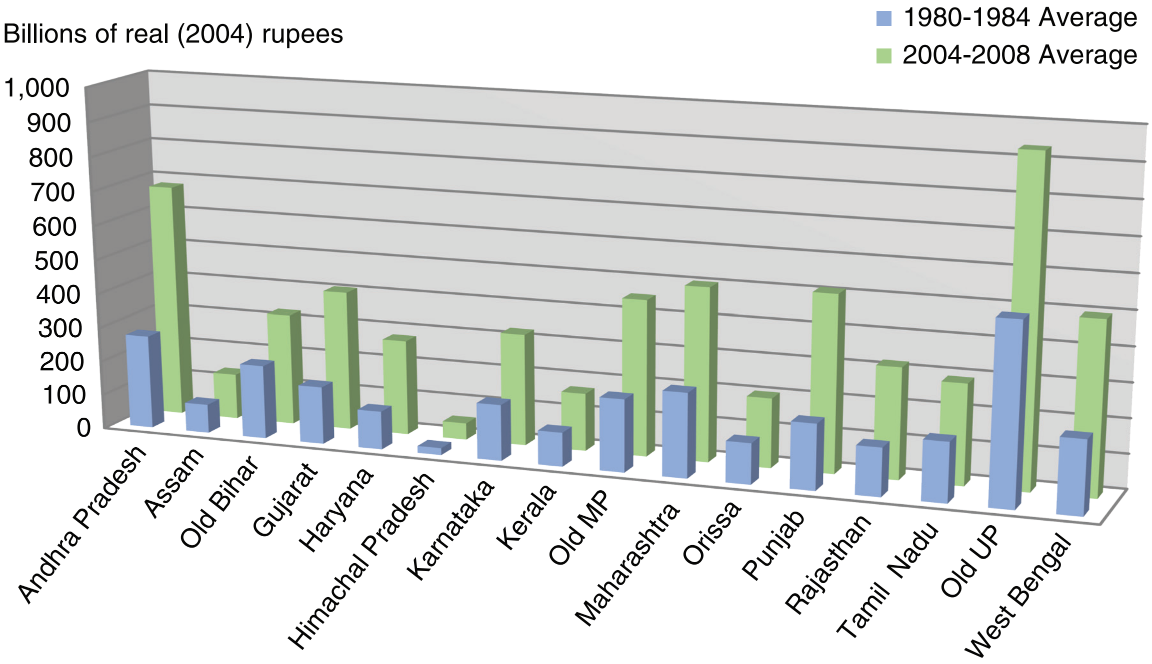
Note: Regional values may not sum to the Indian value because not all Indian States are included.
Source: USDA, Economic Research Service estimates.

---

[4] The exchange rate as of July 3, 2015, is 0.016 U.S. dollars to 1 Indian rupee.

Figure 3

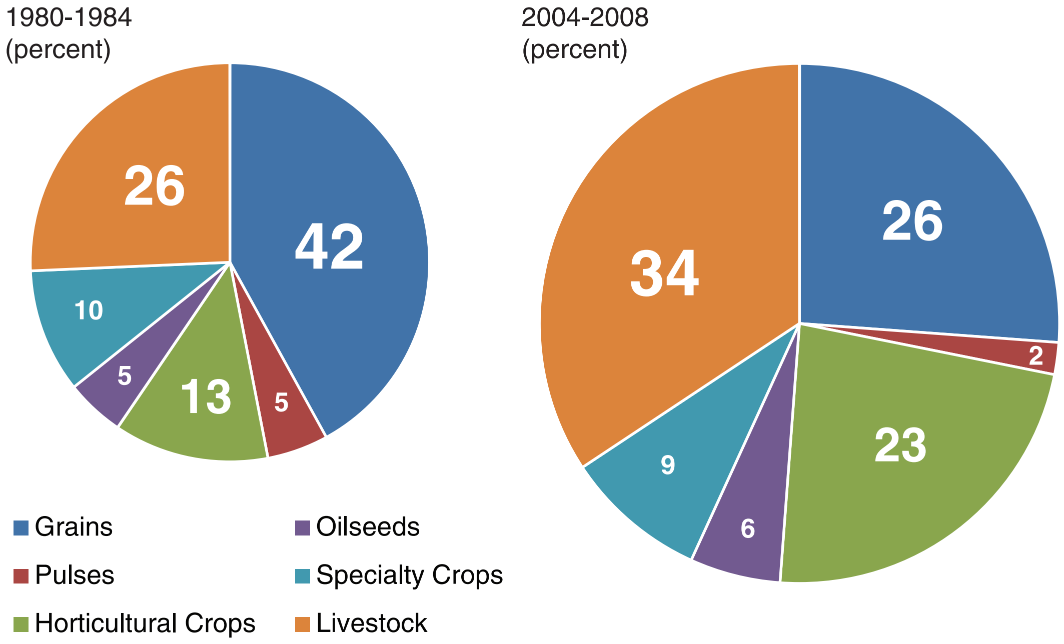
Spatial variation in growth of total agricultural value



Source: USDA, Economic Research Service estimates.

Figure 4

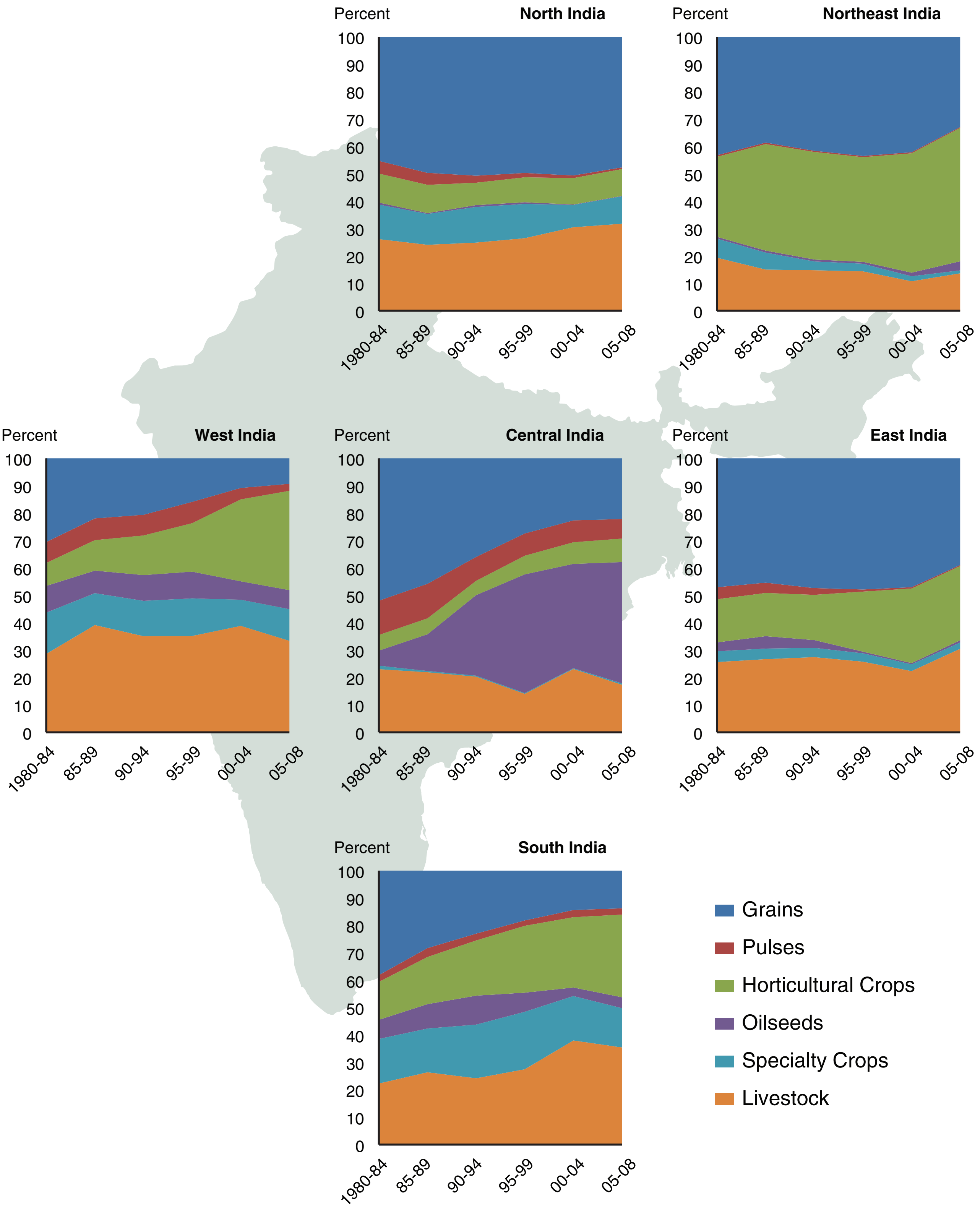
Rising output shares from livestock and horticultural crops



Note: Numbers in the figures reflect percentage shares of output. Shares may not sum to 100 because of rounding.
Source: USDA Economic Research Service estimates.

Figure 5

Regional output production share changes



Note: All data are presented in 5-year averages
Source: USDA, Economic Research Service estimates.

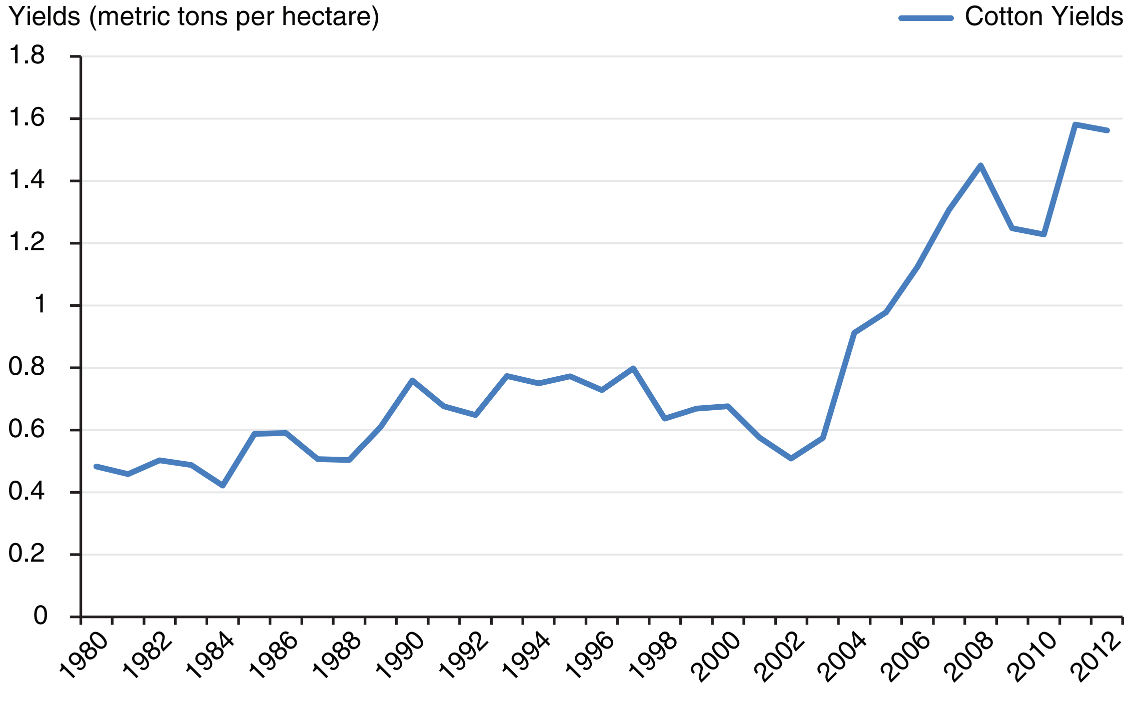
for declining production in other regions. Accelerated horticulture production growth became the norm in the rest of India. Livestock production growth increased in all regions except Central and Northeast India, and the greatest growth occurred in the South.

Cotton production was notable among outputs for its dynamic increase in yields (fig. 6).[5] Between 1980 and 2002, when Bt cotton was officially introduced to India, cotton yields grew by an annual average 1.7 percent.[6] Between 2003 and 2012, yields climbed by an average 8.7 percent annually. States in West India (Gujarat, Rajasthan, and Maharashtra) accounted for 50 percent of India's total 1980-2008 mean cotton production. Together, Gujarat and Maharashtra accounted for the dominant share (86 percent—broken down as 48 percent and 38 percent, respectively) of West Indian production.

The introduction of new Bt cotton technologies may have boosted productivity. Gruere and Sun (2012) note that Bt cotton in India has reduced pesticide applications, helped release female labor from cotton production, and reduced poverty, despite Bt cotton's higher price. Yet some economists have noted that benefits from Bt cotton may be over-attributed to the Bt trait, masking other sources of productivity growth. Ward et al. (2014), citing Gruere and Sun (2012), question whether the Bt trait (which is a damage-abatement technology) or the high-yielding hybrid genetic background (to which the Bt trait was inserted) has been the primary source of yield growth.

Figure 6

Cotton's increasing yields



Note: The cotton measure employed here accounts for both cotton lint and seed.
Source: USDA, Economic Research Service estimates.

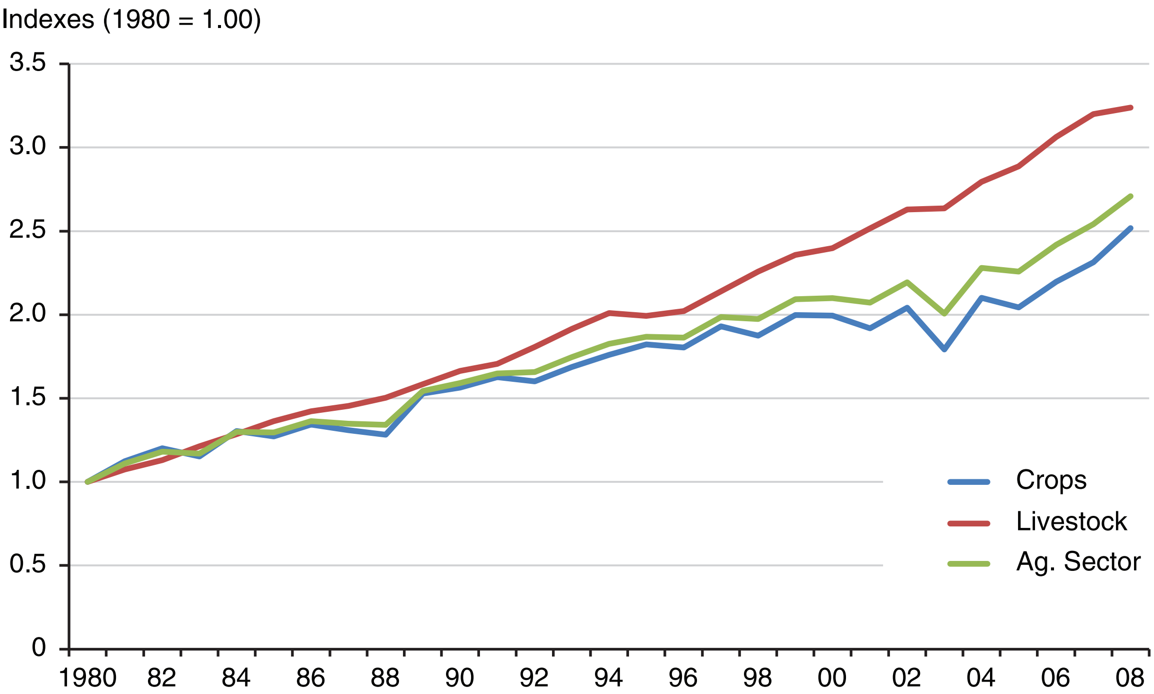
---

[5] We employ United Nations (UN) Food and Agriculture Organization (FAO) growth rates to extend our national cotton estimates from 2008 to 2012.

[6] Cotton measure evaluated here includes both cotton lint and seed.

Figure 7

Crop and livestock chain-weighted Tornqvist-Theil output quantity indexes



Note: The cotton measure employed here accounts for both cotton lint and seed.
Source: USDA, Economic Research Service estimates.

A key contribution of this report (ERR-203) is to integrate high-value commodities into the measure of agricultural output growth. Figures 4 and 5 offer a more complete picture of horticulture crops' increasing share of crop production, nationally and regionally. Animal products increased their share, accounting for an average 27 percent of India's real (2004) gross revenues over 1980-2008.

Animal-product output grew faster and was more resilient in the face of drought than was crop production (fig. 7). From 1980 to 2008, crop production grew an average 2.8 percent annually, while animal commodity production grew 4.0 percent. Growth in milk production (81.3 percent) accounted for the majority of animal production. Growth in other segments included meat production (13.7 percent), egg production (4.9 percent), and wool production (0.1 percent). Growing by an annual average rate of 4.2 percent over 1980-2008, milk production tonnage was largely sourced from buffaloes (55 percent) and cows (41 percent)—the remainder was from goats (4 percent). Buffalo milk production is preferred by Indian farmers because buffalo milk has more fat than that of indigenous cows (an advantage in Indian agriculture's fat-based pricing system) and buffaloes produce more milk than do indigenous cows (Mullen et al., 2005).

We estimate total meat production (see Appendix for details) and find average annual meat tonnage rose by 2.9 percent over 1980-2008. Although India's Hindu population does not generally eat bovine meat, the remaining 20 percent of the population has a growing preference for poultry while maintaining buffalo in their diet, especially in Kerala and East India (Rabobank, 2012). India became the world's largest beef exporter in 2014, although these exports are composed entirely of buffalo meat, which is also referred to as "carabeef" (FAS, 2015).

For perspective on our measure of output growth, we compare it to data from the United Nations (UN) Food and Agriculture Organization (FAO). The FAO compiles annual production estimates from national statistical agencies for 189 crop and livestock commodities. These data are aggregated into a measure of gross agricultural output, using a fixed set of global average prices. Because local prices are not employed, FAO output data lack richness available from data sourced from national accounts. In the present study, national prices are used to compute India's output growth, but State prices are used to compute State output growth. Between 1980 and 2008, FAO's estimation of gross agricultural production, specific to India, increased at an annual average rate of 2.9 percent. The FAO rate is modestly lower than that achieved when using national information—we estimate India's gross output quantity index to have increased at an annual average rate of 3.1 percent. This difference arises from the employed output aggregation weights and the additional attention paid to computing meat production volumes.

Labor Inputs

An annual flow of labor supplied to the agricultural sector can be estimated by accounting for both the number of laborers (stock) and the number of days worked per year. India's farm labor stock grew little over the 1980-2008 period, rising 0.85 percent each year. The number of days worked per year, however, declined by an average 0.27 percent per year. Female laborers in India accounted for 37 percent of India's mean 1980-2008 total labor supply and they worked fewer days per year than did their male counterparts. Once we account for labor's declining days worked, we estimate that India's labor inputs increased, over 1980-2008, by an annual average rate of 0.7 percent.

Because the Indian agricultural sector is labor-intensive, we compare our labor measure with FAO information. FAO's estimate of economically active adults engaged in agriculture is based on projections derived from UN population estimates, International Labour Organization (ILO) labor-force estimates, and an assumption regarding long-term trends in the share of total labor that is primarily employed in agriculture. The FAO estimates do not adjust for the intensity (hours or days worked) of that labor. Thus, the measure adds the implicit assumption of constant average work. Since the present study accounts for the declining number of days worked, it is not surprising that our average annual growth measure of labor inputs (0.7 percent) is substantially lower than FAO's (1.4 percent).

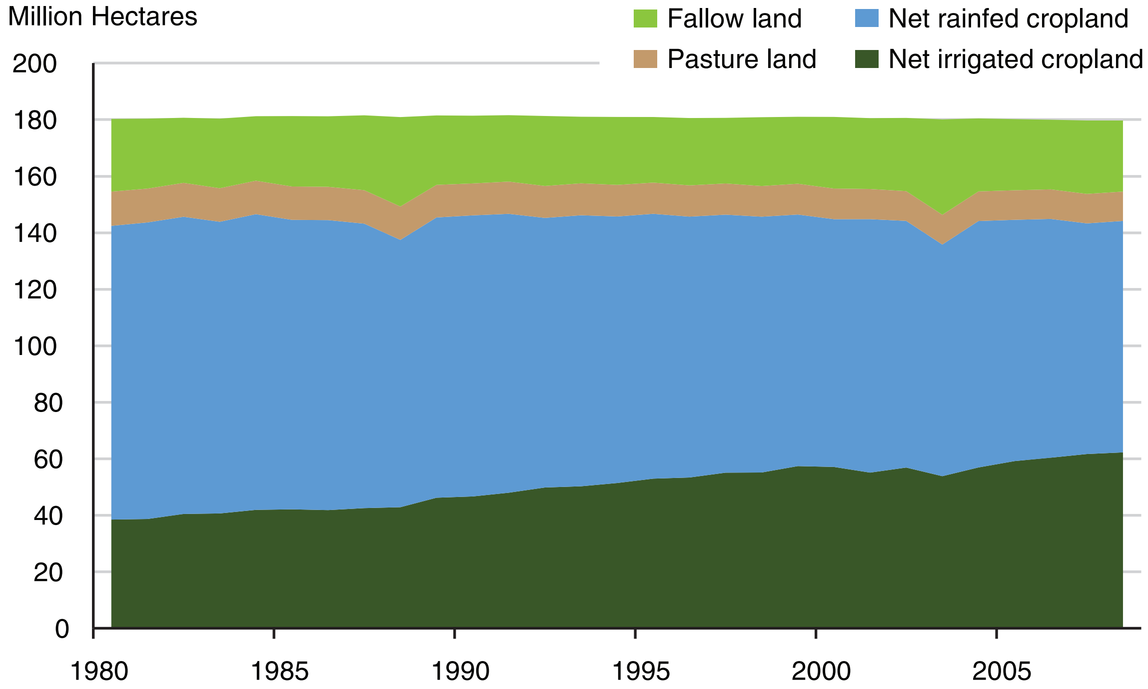
Consistent with Rangarajan et al. (2011) and Azam (2012), our findings confirm that India experienced a post-2004 decline in its number of farm laborers. By our estimates, the number of India's farm laborers declined, on average, by 2.4 percent annually between 2004 and 2009. This decline came during a period in which agricultural wages rose by an average 10 percent each year. Annual wage growth was even higher in Andhra Pradesh (16 percent), Haryana (11 percent), and Rajasthan (18 percent) (GOI, 2009). Rising wages facilitated a release of female labor from agriculture, allowing them to engage in educational or domestic activities (Rangarajan et al., 2011). Recent evidence suggests wages peaked in 2010 and have since declined (GOI, 2015).

Land Inputs

In India, between 1980 and 2008, the practice of annually sowing a plot more than once rose by 65.2 percent, up from 32 million hectares to 53 million hectares (GOI, 2012). Irrigation is the primary factor allowing land to be multi-cropped. To show irrigation's marginal TFP-growth impact, we employ hectares of net land in production rather than gross land in production. Gross land is defined as counting each hectare each time it is sown; net land is defined as counting each hectare once,

Figure 8

Irrigated area's rising share of net cropland in production



Source: Government of India, Ministry of Agriculture and Farmers Welfare, Department of Agriculture and Cooperation, Directorate of Economics and Statistics.

regardless of the number of times it is sown. Double cropping is considered here as a productivity innovation made feasible by irrigation technologies. Thus, production benefits arising from multi-cropping are not accounted for by our land measure, but these benefits appear in our measure of TFP. We then estimate the TFP impact of expanding irrigated area.

Four land types are aggregated: net irrigated area, net rainfed area, pasture land, and fallow land. Net land in production did not increase over 1980-2008 (fig. 8). In fact, it declined by an average annual rate of 0.02 percent. This aggregate measure obscures changes among land types. For instance, pasture land declined an average 0.6 percent annually, while net irrigated area increased by 1.7 percent.

Notable in figure 8 are the dips in rainfed area in years 1988 and 2003. These were drought years. Irrigated area, however, did not decline as sharply, revealing the improved resilience achieved through irrigation. Four types of irrigation are commonly employed in India: canal irrigation, well irrigation, tank irrigation, and "other," which generally refers to obtaining water from sources such as waterfalls and streams. As detailed in the following discussion of production inputs, these irrigation types are a focus of our policy analysis.

Intermediate Inputs

Intermediate inputs consist of active ingredients of inorganic crop fertilizers and electricity consumed by agriculture. Electrical power consumption on Indian farms has increased by an average 7 percent annually. Electrical power consumption often strongly correlates to water withdrawals because most irrigation pumps, especially outside of East India, employ electric pumps (Akermann, 2012). Akermann notes that by 2003, the highest State shares of electric pumps are in Karnataka (89 percent), Maharashtra (87 percent), Andhra Pradesh (78 percent), and Kerala (85 percent).

Fertilizer in the present study includes nitrogen, phosphate, and potassium. Over 1980-2008, nitrogen accounted for 66 percent of mean fertilizer applications; phosphate, for 24 percent; and potassium, for the remaining 10 percent. Some in the media have attributed nitrogen's dominant share as a distortion to the market caused by politically sensitive fertilizer subsidies (Anand, 2010). In 1992, both phosphatic and potassic fertilizers were removed from the price control subsidy program, leading to a rapid rises in their prices (Mullen et al., 2005).

Capital Inputs

Livestock and machinery capital inputs are included in the present study. Livestock capital accounts for the on-farm stock of animals and includes cattle, buffalo, sheep, goats, pigs, and poultry. Little growth occurred in cattle, sheep, goat, and pig stocks, each achieving an average annual growth rate between 1980 and 2008 below 0.02 percent. Buffalo and poultry stocks, however, rose by 1.8 percent and 4.0 percent, respectively. Following Hayami and Ruttan (1985, p. 450), we converted animals to "cattle equivalents" to allow for aggregation when accurate animal service prices were not available. India's on-farm stock of cattle-equivalent animals increased by 0.8 percent annually between 1980 and 2008.

We proxied for machinery capital by evaluating the number of tractors in use. Growth in machinery capital was quite rapid, reaching an average annual 8 percent between 1980 and 2008. Across States, the average annual rate of growth was greatest in Orissa (15 percent), Himachal Pradesh (13 percent), Old Madhya Pradesh (11 percent), and Rajasthan (10 percent). Nearly all investment in machinery capital was private by farmers; the World Bank (2014b) shows public capital investment stagnated between 1993 and 2003, then rose slightly until 2007, and held steady until 2011. Conversely, private capital investment rose sharply after 1995, climbing unabated until 2009.

TFP Growth of Indian Agriculture

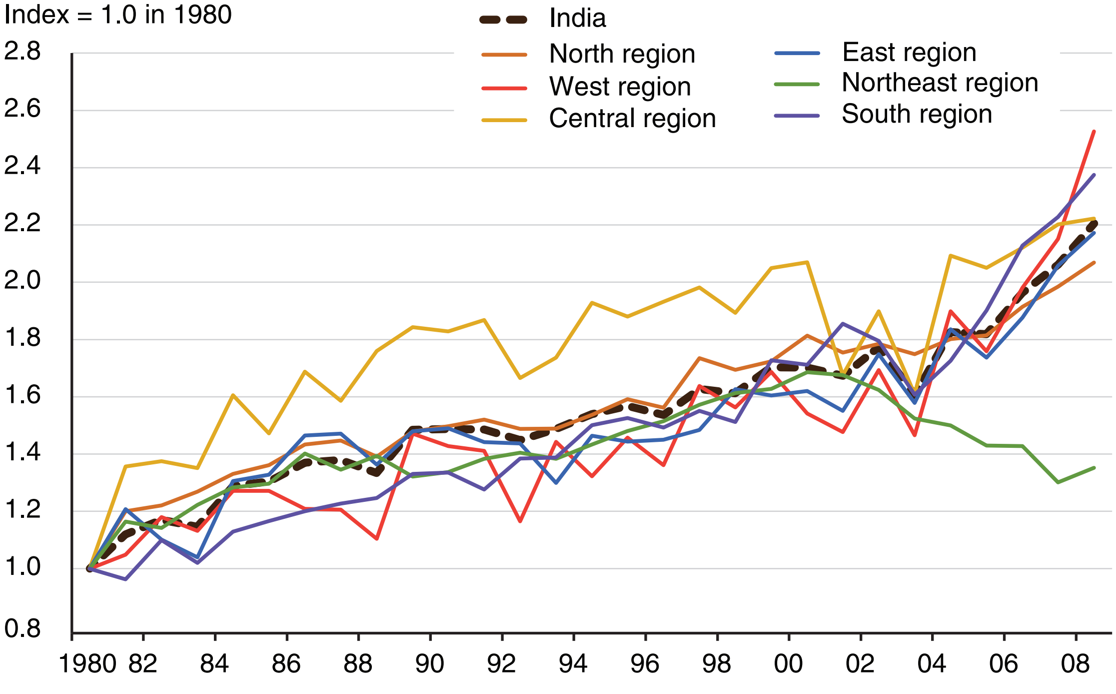
We estimated annual indexes of agricultural TFP growth over 1980-2008 at the State, regional, and national levels as the value-share weighted growth of outputs less the value-share weighted growth of inputs (see Appendix, Eq. 1 for details). India's annual average agricultural TFP growth rate, over 1980-2008, was 2.07 percent (fig. 9). TFP accounted for 66 percent of output growth (3.14 percent, annually); input growth (1.07 percent, annually) accounted for the remainder of output growth.

India's TFP growth rate has varied not only over time, but also by region. Over the 1980-2008 period, India's North achieved an annual average TFP growth rate of 1.86 percent, led by Punjab (2.08 percent) and Haryana (2.07 percent apiece), followed by Old Uttar Pradesh (1.82 percent) and Himachal Pradesh (1.47 percent) (fig. 10). East India achieved a slightly slower annual average TFP growth rate of 1.90 percent. TFP growth there, however, was less uniform: West Bengal achieved strong TFP growth of 2.92 percent, while Orissa (0.88 percent) and Old Bihar (1.32 percent) lagged behind. Notably, all East Indian States achieved strong TFP growth after 2004 (fig. 11).

West India, conversely, achieved slower-than-national growth until 2004, when growth started to exceed the national average (fig. 12). Between 1980 and 2008, annual average TFP growth in the West was 2.16 percent, but lagged behind most of India before accelerating rapidly in the mid-to-late 2000s. The wide productivity growth swings of the West Indian region presented in fig. 12 typify Indian rainfed agriculture, in which production responds to variable rainfall patterns. While Rajasthan's annual average TFP growth (2.56 percent) was the fastest among West Indian States, Maharashtra (2.45 percent) and Gujarat (2.19) followed closely behind.

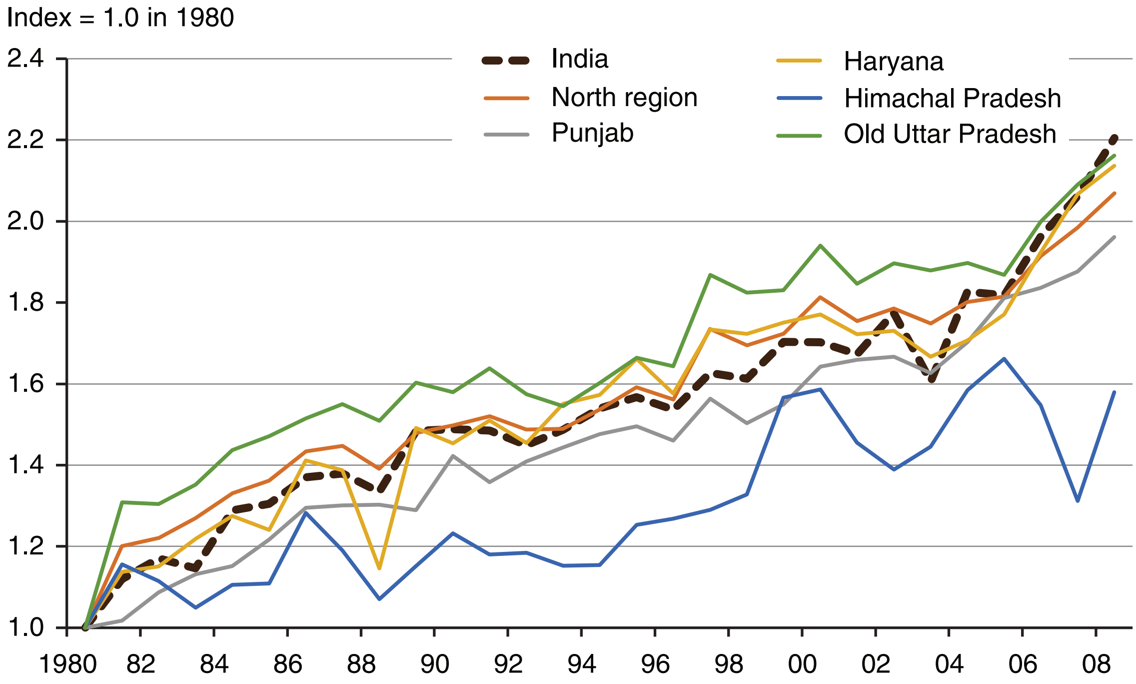
Figure 9

National and regional total factor productivity growth, 1980-2008



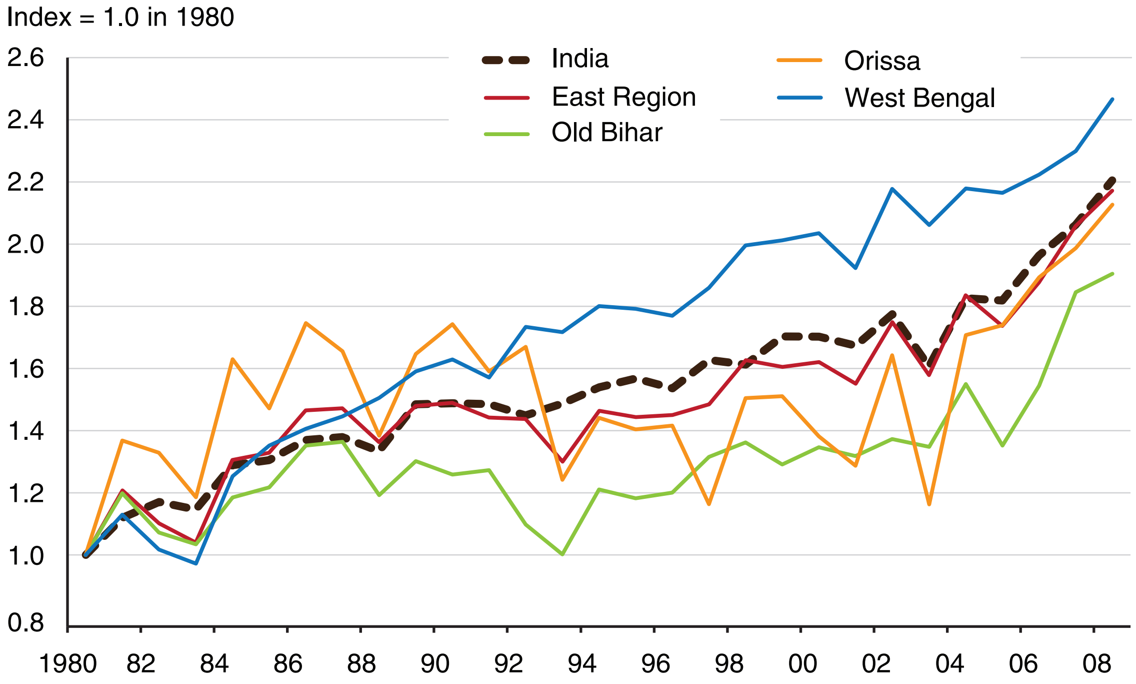
Source: USDA, Economic Research Service estimates.

Figure 10
National and North India's total factor productivity growth, 1980-2008



Source: USDA, Economic Research Service estimates.

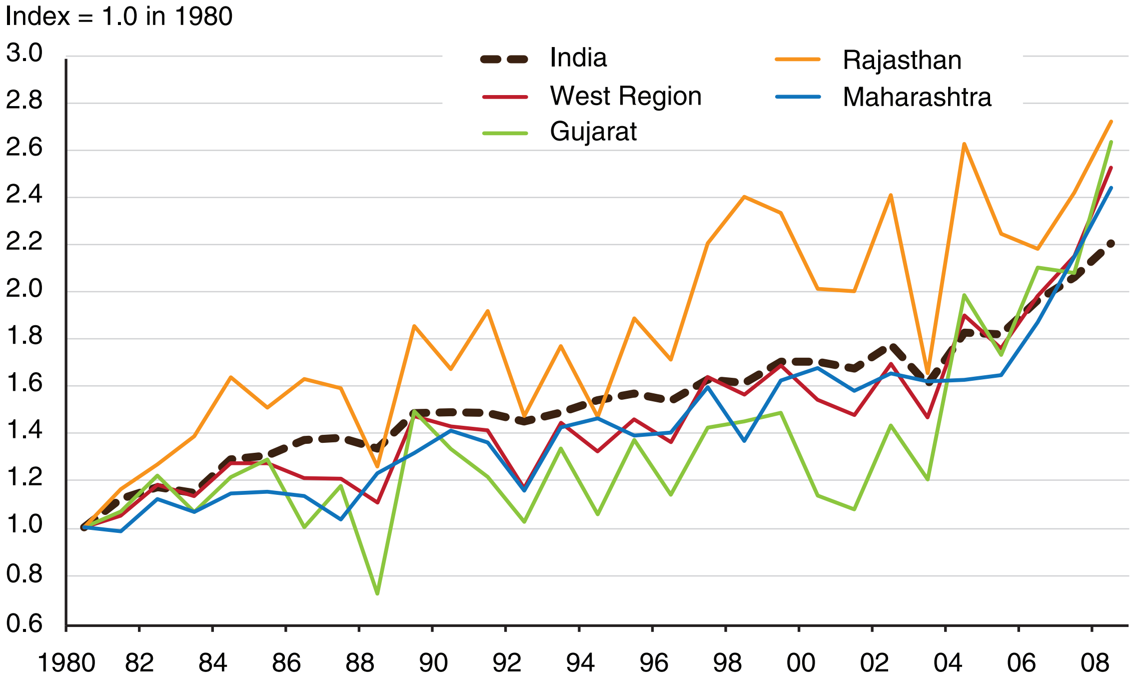
Figure 11
National and East India's total factor productivity growth, 1980-2008



Source: USDA, Economic Research Service estimates.

Figure 12

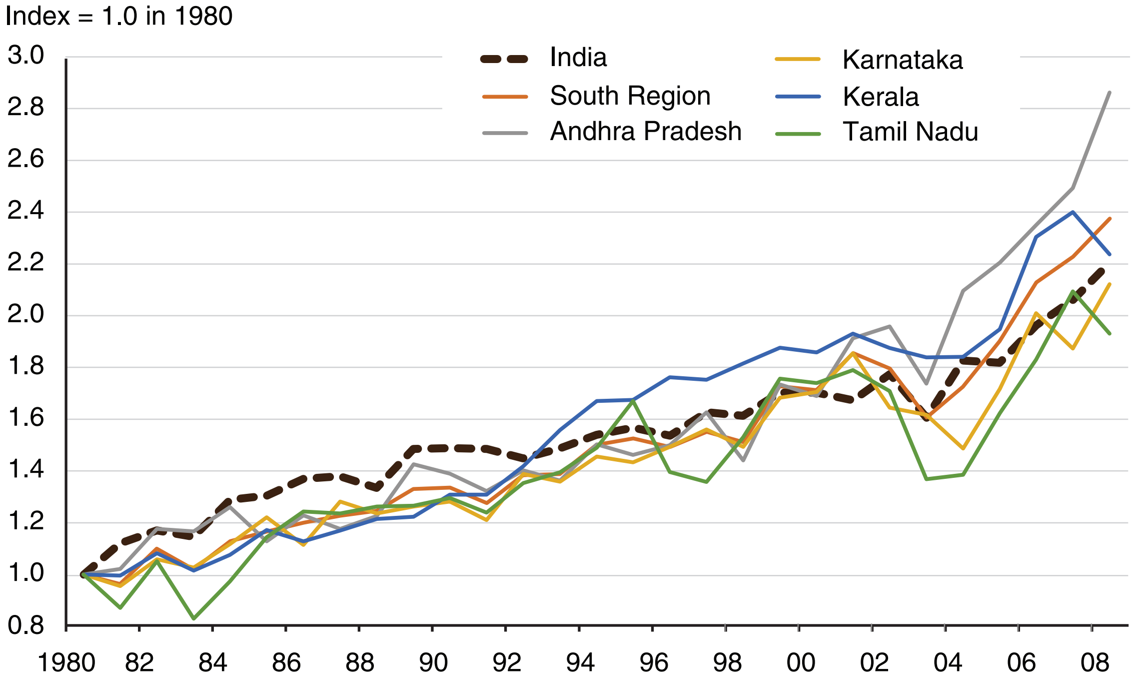
National and West India's total factor productivity growth, 1980-2008



Source: USDA, Economic Research Service estimates.

Figure 13

National and South India's total factor productivity growth, 1980-2008



Source: USDA, Economic Research Service estimates.

Policy reforms and new technology adoption likely played a role in West India's late growth surge. For example, State lawmakers in Gujarat amended the Agricultural Produce Market Committee Act to waive marketing fees and allowed private companies direct contact with horticultural producers (GHI, 2014). Further initiatives in Gujarat State that likely stimulated agricultural productivity were the promotion of micro-irrigation systems and the Jyotigram Scheme. The Gujarat Green Revolution Company was created to advance drip irrigation technologies through subsidized loans and a streamlined administrative process. The Jyotigram Scheme separated agricultural from non-agricultural power supplies, providing farmers 8 hours of full-voltage power at anticipated times, and limited competitive pumping for groundwater in a State with primarily rainfed agriculture (64 percent) (Gulati et al., 2009).

South India achieved the country's fastest TFP growth. Over 1980-2008, annual average TFP growth in the South reached 2.66 percent. While all South Indian States achieved faster-than-national growth, there was substantial difference among them (fig. 13). Andhra Pradesh and Kerala experienced rapid 1980-2008 annual average growth (3.04 percent and 3.12 percent, respectively), while Tamil Nadu and Karnataka experienced slower, but still strong, growth (2.45 percent and 2.40 percent, respectively). Common among these States was broad diversification to high-value outputs, strong growth in specialty crops, such as cotton and sugarcane, and since 2004, flat or negative input growth, driven by the aforementioned post-2004 decline in India's number of farm laborers.

Factors Hypothesized To Explain India's Agricultural TFP Growth

We hypothesized that a variety of policies contributed to India's 1980-2008 productivity growth. Evidence from the literature suggests that over 1980-2008, yield growth rather than diversification to higher valued crops was the main determinant of crop output growth (Rada, 2013; Birthal et al., 2008).[7] With that in mind, we focused on investments in three technology variables, international public research, national public research, and private research. We suspected public and private agricultural research investments stimulated long-term technological change across a spectrum of farm commodities, allowing the sector to respond effectively to both poorer consumers' grain demands and wealthier consumers' high-value food demands. Because agricultural research is mainly conducted on primary crops, as noted previously, it is unclear if and how the administrative transition presently occurring in the SAUs will allow the research system to respond to increased demand for high-value commodities.

We modeled research-spending's effects on TFP growth by creating "knowledge capital"—or a stock of knowledge generated by the accumulation of past annual research investments.[8] Knowledge capital accumulates with a lag such that the effect of any specific year's research spending is spread over several decades before knowledge generated is entirely translated into higher TFP growth (Alston et al., 1995). National and international public agricultural research investments are detailed below, followed by our approach to measuring knowledge capital. We proxy for data on private research spending (which was unavailable) with a trend variable. Other investments detailed below include those in irrigation infrastructure, transportation infrastructure, and human capital development.

National Agricultural Research and Higher Education Spending

Annual public agricultural research and higher education expenditures were thin in the 1960s. SAU investments, measured in 2004 constant rupees, were 6.5 times larger than public investments made to ICAR (fig. 14). The dearth of Federal investment during the 1960s coincided with a shift to centralized ICAR funding and accelerated funding to SAUs (Pal and Singh, 1997). Reorganization of ICAR in 1973 and substantial increase of public investment in the Fifth Plan (1974-78) initiated a sharp uptick in research spending. Between 1974 and 2008, SAU research expenditures grew by an annual average 4.7 percent, while ICAR expenditures grew by an annual average 5.4 percent.

India's SAUs do not, however, receive equal funding. Their levels depend on how well their research integrates with national agricultural development priorities. Examining 1980-2008 mean research expenditures by Indian State shows that Maharashtra and Old Uttar Pradesh achieved the highest mean levels of research spending, although they both experienced relatively slow growth (fig. 15).

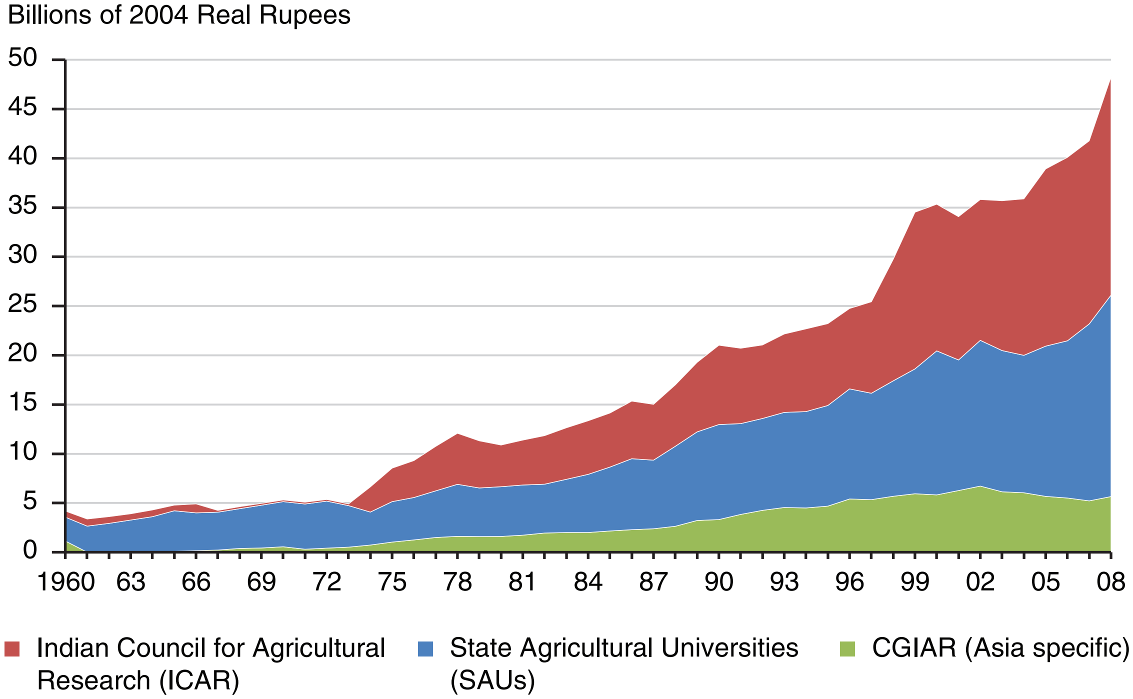
---

[7] Remaining proportions of crop output growth are attributed to different factors. Rada (2013) decomposes crop output growth into diversification, yield growth, and area expansion; Birthal et al. (2008) decomposes it into diversification, yield growth, a price effect, and an interaction term.

[8] It is important to note that—because agricultural research in India has focused on other issues apart from yield-enhancing technologies, such as reducing disease and pest risk and responding to consumer preferences—the estimated relationship between "knowledge capital" and TFP growth may not be the best indicator of the research system's effectiveness.

Figure 14

ICAR, SAU, and CGIAR (Asia specific) research and development investments



Note: CGIAR = Consultative Group on International Agricultural Research.
Source: USDA, Economic Research Service estimates.

Conversely, Haryana and Kerala had relatively low mean levels of research spending, yet experienced the fastest growth. Other States, such as Andhra Pradesh, showed average research-spending levels and growth rates that were both relatively high.

Evenson et al. (1999) test various research stocks (i.e., knowledge capital variables), finding that India's research investments in any given year generated knowledge and technology benefits for 27 years. For example, new varietal technologies generated in 2007 would have benefited from research investments made since 1980. We revisit the Evenson et al. research stock estimates because they did not include the impact of international spill-ins despite strong linkages between national and international research efforts.

International Agricultural Research Spending

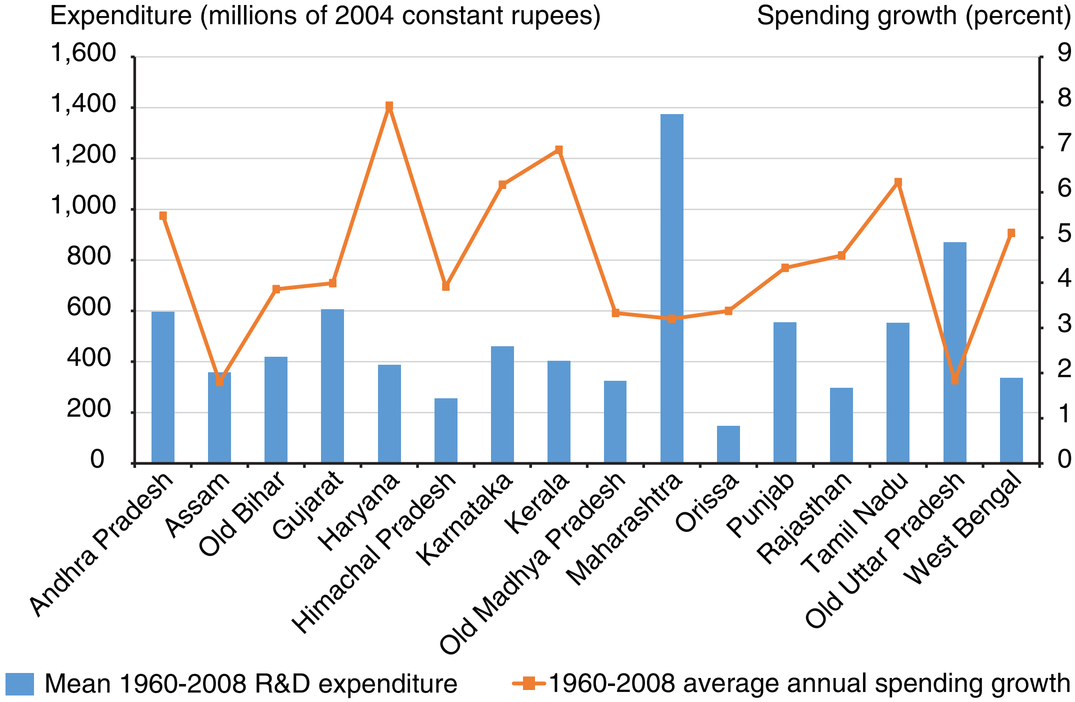
Funding for CGIAR research centers is presented relative to ICAR and SAU expenditures (see fig. 14). Focusing strictly on the CGIAR research directed toward Asia between 1960 and 2011, we find research expenditures grew by an average annual rate of 8.8 percent.[9] Growth of international research investments slowed dramatically: measured in 2004 constant rupees, CGIAR investments in Asia grew by 6.8 percent annually over 1980-1990, falling to 5.4 percent annually over 1990-2000, and then dramatically falling to -0.01 percent over 2000-2010. Although CGIAR research investments have rebounded strongly in recent years, the long-term growth deceleration of CGIAR investments specific to Asia is serious cause for concern. International research has been shown to have a significant effect on agricultural TFP (Rada and Fuglie, 2012; Fuglie and Rada, 2013).

---

[9] Measured in real (2004 constant) rupees.

Figure 15

Variations in State Agricultural University (SAU) funding and growth



Notes: R&D = research and development.
Source: USDA, Economic Research Service estimates.

Private Research Contributions

Embodied in each new technology approved for sale by the Indian regulatory system might be huge investments by multinational companies to develop similar products in other countries—technologies that are adapted to local conditions at substantially lower cost than if they had originally been developed in and for India. As noted above, germplasm embodied in inbred cultivars may have resulted from public international and national research spending. These inbred lines are often used by private research firms to create new hybrids with enhanced traits. Because the impact of the private sector on TFP growth depends on these other interacting factors, and because private research spending has risen, we model private research as another factor which may be proxied as a time trend. Pray and Nagarajan (2014) estimate that a total of $174 million (2005 U.S.$) of private research was conducted in India in 2008-09, compared to over $538 million of public research. This 24-percent private-research share of total research expenditures compares closely with the World Bank's (2014b) estimated growth in private spending in India from 17 percent in 1994-95 to 26-30 percent by 2008-09.

Measuring Knowledge Capital From Research Spending

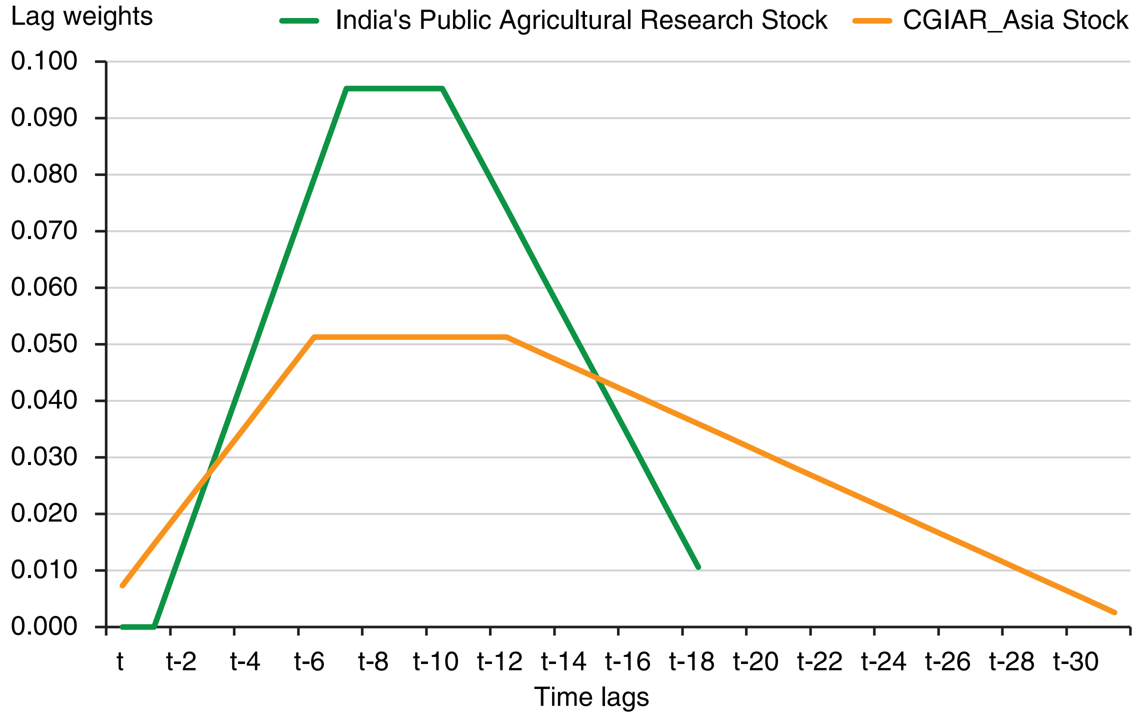
Applied or adaptive research tends to have shorter lags than basic research; and both basic and applied research can have gestation lags where no impacts are seen for several periods after research investments have been made (Oehmke and Schimmelpfennig, 2004; Alston et al., 2010). Following that gestation period, the lagged impact of research spending gradually rises over the course of an adoption period, until the effects of those research investments peak—the effects of some research sustaining that peak longer than other research—and then diminish, eventually ending in technology obsolescence (Alston et al., 1995).

To estimate India's agricultural research stocks from annual research expenditures, we test combinations of individual lags to determine the appropriate peak effect for both national and international research investments. Drawing from those results, we test for lag length of the technology adoption period, period of maximum effect, and the period of technology obsolescence (Huffman and Evenson, 1992; Huffman, 2009). Trapezoidal structures have been shown to better characterize research's lagged impact on productivity than do polynomial distributed lag (PDL) structures (Alston et al., 2010). Specifically, the trapezoidal distribution could have different rates of uptake at the beginning (i.e., technology adoption) from declines at the end (i.e., technology obsolescence), and may more accurately characterize the period of maximum impact than a PDL (See the Appendix for details).

We estimate India's national agricultural research expenditures to have a 19-year lag, of which gestation occurs for 2 years, research expenditure effects gradually increase for 5 years, those effects peak for 4 years, then diminish and finally terminate after another 8 years through technology obsolescence (fig. 16). International research expenditures are estimated to have a much longer lag of 32 years, of which there are 6 years of increasing impact, 7 years of maximum impact, and 19 years of diminishing impact prior to technology obsolescence (see fig. 16). These lags differ from Evenson et al.'s (1999) 27-year lag that contained 9 years of rising impact, 9 years of maximum impact, and 9 years of diminishing impact. Notably, the average of the national and international lag structures is 25.5 years, very close to Evenson et al.'s 27-year estimate. Our models suggest that, in general, India's national public research system developed more applied research technologies, and CGIAR research systems developed more basic research technologies.

Figure 16

International and national agricultural research stock estimates



Note: CGIAR = Consultative Group on International Agricultural Research.
Source: USDA, Economic Research Service estimates.

Irrigation Infrastructure

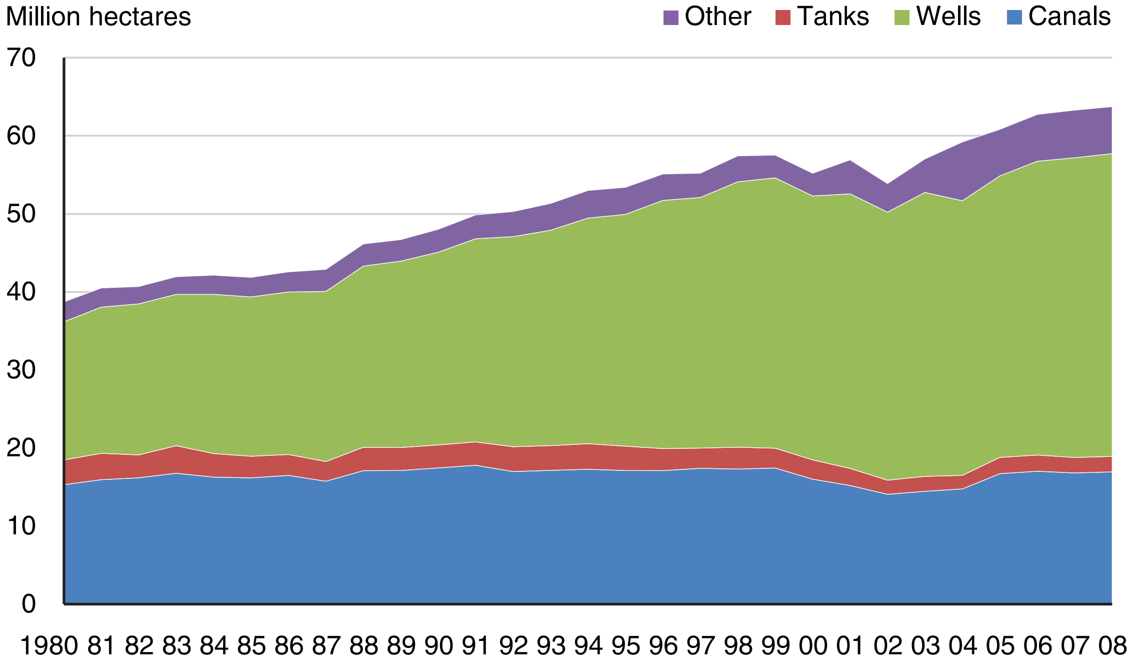
Sources of India's irrigated area vary among canal, well, tank, and "other" water. India uses 13 percent of the world's extracted water, and 87 percent of that water is used in irrigation (GHI, 2014). In the 1980s, India was the world's third-largest groundwater user (Akermann, 2012, p. 245); today it is the largest groundwater user (Shankar et al., 2011). Since 1980, groundwater from wells has been the dominant source of irrigation and has seen the greatest growth (fig. 17). In 1980, near parity existed between irrigation from wells and from canals; 46 percent of all irrigated area was sourced from wells; 40 percent was sourced from canals. By 2008, groundwater-well irrigation accounted for 61 percent of total irrigated area.

Canal-sourced irrigated area, on the other hand, declined in its share of total area irrigated, falling an average 1.8 percent each year from 1980 to 2008. India's shift away from surface-water irrigation is not surprising, given that end users of public canal irrigation may or may not receive water, depending on supply and up-river withdrawals, and given the geographic demands of accessing canal water.[10] [11]

Pointing to irrigation's role in double cropping, Gulati et al. (2009) show that, in Gujarat, gross irrigated area between 2000-01 and 2006-07 expanded most rapidly under wheat, cotton, and fruits and vegetables. Although wheat-irrigated area expanded fastest, the presence of irrigation may have drawn farmers to horticulture. In Tamil Nadu State, output diversification was found to

Figure 17

India's irrigated area, by source



Source: Government of India, Ministry of Agriculture and Farmers Welfare, Department of Agriculture and Cooperation, Directorate of Economics and Statistics.

---

[10] One reviewer notes the related issue of unlined canals potentially helps recharge groundwater stocks in some areas.

[11] Tank's irrigated area share, averaged over 1980-2008, has been only 5 percent, and other has been 7 percent. Due to their low shares, they are not separately evaluated here.

boost incomes in the presence of irrigation but to have no impact in rainfed areas (Amarasinghe et al., 2009). These authors note that, lacking consistent water supply, diversification in these areas remained as a form of crop insurance rather than a source of income. Further, the advanced drip technologies applied in Gujarat as part of the Gujarat Green Revolution Company's promotion of micro-irrigation schemes have been predominately applied to high-value crops (Gulati et al., 2009).

Rural Road Infrastructure

Rural roads support agricultural development by reducing transportation costs, lowering input prices paid by farmers, and raising the amount of output that arrives to market by reducing spoilage (Calderón and Servén, 2004). Road densities were chosen to model the effect of infrastructural investments on productivity growth because, in India, roads are still the primary means of transporting agricultural outputs and inputs to farmers. Yet it is unclear from the literature whether roads have contributed to productivity in India. Fan et al. (1999) find a positive road-TFP elasticity at the State level. Kumar et al. (2004) find a positive infrastructure-TFP elasticity using an index to account for transportation, energy, irrigation, banking, primary education, and health indicators at the district level. However, Kumar et al. (2013) find no statistically significant relationship between roads and TFP or between an infrastructure index and TFP at the State level. These authors hypothesized that many Indian States may now have enough roads that additional road investments may no longer stimulate their productivity growth.

Rural Public Education

Our measure of human capital is the rural population's average number of years of schooling. As people's education improves, so too does their ability to adopt new technologies and agricultural practices. According to India's National Sample Survey (NSS) data, the average rural Indian in 1980 had less than 2 years of schooling, and by 2011, the average had risen to 4.5 years. Such an average obscures the variable investments to public education among Indian States. For instance, over 1980-2008, the average years of schooling for a rural-dwelling person ranged from 6.3 years in Kerala to 2.4 years in Rajasthan. Moreover, those respective rankings are consistent over time. India's low rural educational achievement is on par with many Sub-Saharan African countries, which in 2005, for the whole region, had an average level of rural schooling of 5 years (Fuglie and Rada, 2013). It is likely that the lack of rural education has stunted potential agricultural gains.

Explaining India's Agricultural TFP Growth

Coefficient estimates from the multivariate regression specified in Appendix Equation 4 are presented in table 2. Our discussion of model results focuses on model specifications (5) and (6) of table 2. Millimeters of rainfall, to account for precipitation variations, and a time trend, to account for factors inseparable from other difficult-to-measure variables which incrementally increase with time, were included to test for variable identification. For example, the inclusion of a time trend in (3)–(6) provided evidence of the degree that model specifications (1) and (2) were sensitive to the inclusion of unmeasured variables that have trends. The time trend in specifications (3)–(6) can be interpreted as the mean effect of measured and unmeasured trended variables.

Policy Effects on Agricultural TFP Growth

We focus first on India's public agricultural technology variable—national public research and education *(NARE)*. Browsing across the table 2 model specifications, we see that the *NARE* estimate is marginally reduced once we include a time trend, but its general stability over specifications boosts our confidence in the result.[12] With a focus on table 2's specification (5), in which regional dummy variables are multiplied by the research variable to capture regional policy impacts, results point to uneven benefits generated by India's long-term research spending. The *NARE* estimate in this specification is relative to the Indian East (the omitted region), such that a positive and statistically significant *NARE*-regional interaction-dummy estimate indicates a more rapid change than achieved by the omitted region's agricultural research impact. Thus, while a 1-percent increase in India's knowledge capital accelerated TFP in the East by 0.12 percent, it accelerated TFP in the North, Center, and West by 0.13 percent. The South and Northeast regions did not show statistically different effects from the East.

At the national level, when the regional effects are summed, we find a 1-percent increase stimulated TFP by 0.15 percent. The magnitude of India's national public research-and-education-TFP elasticity has ranged in the literature. Evenson et al.'s (1999) TFP study estimates a public research-TFP elasticity of 0.05 using district-level data. Fan et al.'s (1999) study estimates a public research-TFP elasticity of 0.30 using State-level data. Kumar et al.'s (2013) study estimates a public research-TFP elasticity of 0.20 using State-level data. The present study's marginal estimate of 0.15 is thus well within the boundaries presented by the literature.

Evidence supporting our finding includes demonstrated economic benefits of high-impact seed technologies adopted to mitigate such stresses as excess moisture, water logging, and salinity and to increase drought-, cold-, and high-temperature tolerance.[13] In the case of rice, Ward et al. (2014) note that innovations that improve yields, duration of harvested farm products, or stress tolerances mostly originate from public research. Myrick et al. (2014) show that, in 2009, public national and international collaborative research efforts to combat the papaya mealybug generated between $121 million and $309 million of economic benefits in India for papaya, tomato, eggplant, mulberry, and cassava production. The net present value of these benefits over 5 years range from $524 million to

---

[12] One reviewer questions whether new information could be obtained from an interaction of public international and Indian agricultural research variables. We tested this interaction variable, but it was not included because it lacked statistical significance.

[13] For other examples of new varietal technologies developed by India's public research system, see http://www.iari.res.in/?option=com_content&id=192&Itemid=538.

Table 2

Explaining India’s agricultural total factor productivity growth, 1980-2008

Model Specification:	1	2	3	4	5	6
Dependent Variable:	Ln.TFP	Ln.TFP	Ln.TFP	Ln.TFP	Ln.TFP	Ln.TFP
Ln.NARE	0.164***	0.166***	0.130***	0.127***	0.118***	0.127***
Ln.CG_Asia	0.114***	0.110***				
t			0.013***	0.013***	0.015***	0.014***
Rain	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***
Ln.Irrig	0.057***	0.055***	0.052***		0.042***	0.036***
Ln.Irrig_Wells				0.033**		
Ln.Irrig_Canal				0.024*		
Schooling	-0.077**	-0.070*	-0.097**	-0.090**	-0.111***	-0.110***
Schooling^2	0.011***	0.010***	0.011***	0.010***	0.011***	0.011***
Ln.Infra_Roads		-0.013	-0.011	-0.016		
Ln.NARE*Central					0.010*	
Ln.NARE*Northeast					0.001	
Ln.NARE*South					0.006	
Ln.NARE*West					0.010**	
Ln.NARE*North					0.011**	
Ln.Irrig*Central						0.012
Ln.Irrig*Northeast						0.011
Ln.Irrig*South						0.005
Ln.Irrig*West						0.012*
Ln.Irrig*North						0.012*
Constant	-2.923***	-2.836***	-28.18***	-27.33***	-31.31***	-29.77***
Observations	464	464	464	464	464	464
Number of States	16	16	16	16	16	16
R-squared:						
within	0.752	0.752	0.757	0.758	0.757	0.756
between	0.144	0.145	0.172	0.191	0.229	0.241
overall	0.596	0.598	0.606	0.601	0.640	0.639

Note: Statistical significance is given by * = 90% significance, ** = 95% significance, *** = 99% significance. "Ln." reflects the variable is in log form. "Central," "Northeast," "South," and "West" reflect regional dummy variables. The East region was omitted. NARE = National Agricultural Research and Education. CG_Asia = International agricultural research expenditures (CGIAR) specific to Asia. Irrig. = irrigation.

Source: Authors’ estimates.

$1.34 billion. Thus, although a common criticism of India’s public agricultural research agency is that it is ineffective, the evidence in recent literature underlines the value of public research investments. Moreover, private research often builds on publicly developed inbred varieties, indicating a strong role for public research in supporting private research innovation.

India operates a mainly rainfed agricultural system and has long invested in irrigation capital to mitigate weather risk and stimulate production. We investigate irrigation’s effect on TFP in two ways. First, we differentiate between the effect on TFP from groundwater irrigation supplied by wells and from surface-water irrigation supplied by canals. Second, we test whether expanding total irrigated area affects TFP equally across regions and compute the national-average effect on TFP of expanding total irrigated area.

Table 2's specification (4) indicates that expanding irrigated area served by wells accelerates TFP by 0.03 percent, while expanding irrigated area served by canals accelerates TFP by 0.02 percent. Indian farmers' shift to well irrigation has expanded area which may be double cropped, boosting productive capacity beyond what has been achieved through canal irrigation. Specification (6) shows that expanding total irrigated area benefits TFP more in the Indian North and West than in the rest of the country. Specifically, a 1-percent increase in total area irrigated raises TFP by 0.05 percent in the Indian North and West, but only by 0.04 percent in other regions. Summing these effects, we find that boosting total area under irrigation by 1 percent increases India's agricultural TFP growth by 0.06 percent. Our irrigation estimate compares favorably with those from the literature: Fan et al. (1999) estimate an irrigation-TFP elasticity of 0.03; the World Bank (2014b) estimates an irrigation-land productivity (real output per hectare) elasticity of 0.09; and Evenson et al. (1999) estimate an irrigation-TFP elasticity in India of 0.18.

When we further evaluate how an increase in years of schooling may affect agricultural TFP, we find that a 1-year increase evaluated at the mean of the data (in this case, 3.4 years of schooling) decelerates TFP growth by an average of 0.09 percent across model specifications. Yet we find higher levels of education, as reflected by the $Schooling^2$ variable, have a positive influence on TFP. Using these parameter estimates, we investigate how many years of rural public education are required before the relationship between schooling and TFP turned positive.[14] According to our calculations, once a per capita average education level of 4.3 years is reached, the effect of more education on TFP is positive. These results highlight that low rural education levels have acted as a drag on TFP growth, but that rural human capital investments on average support TFP growth if the per capita average education level is more than 4.3 years.

Other variables of interest include public investments in international agricultural research (*CG_Asia)* and rural roads *(Roads)*. It is difficult to isolate the effect of international public research from the effects of other trending factors on TFP growth. International public research is statistically significant in the first two specifications, so we can confidently assert that these investments are correlated with TFP growth. However, international public research is omitted from the last four specifications because of its collinearity with the time trend (table 2).[15] The end result is that the individual effect of international public research is entangled with other trending factors, such as private investment in agricultural research.[16]

Of all the policies evaluated, only investments in road infrastructure do not correlate with productivity. The roads variable is statistically insignificant across all models. It is likely that, as argued by World Bank (2014b), India's 16 States already have sufficient rural road density. Thus, marginally increasing rural road infrastructure would not measurably affect farm TFP growth.

---

[14] We compute the average number of years required for public education investments to positively affect TFP by taking the formula for the derivative of TFP with respect to *Schooling* and setting it equal to zero. Solving for the mean of *Schooling* pinpoints the number of years of education required for *Schooling* to have no effect on TFP. Values greater than that solved mean estimate indicate positive influences on TFP, and values smaller than the estimate indicate negative influences, given that *Schooling*'s impact on TFP decreases at an increasing rate.

[15] That CG_Asia was dropped is no surprise in light of its 0.99 pairwise correlation with the time trend.

[16] While private research spending has risen rapidly, especially for seed development, the inclusion of a squared time trend indicates trending factors, in aggregate, have not accelerated at an increasing rate. One reason may be research spending's long gestation period before on-farm technologies that boost TFP become available.

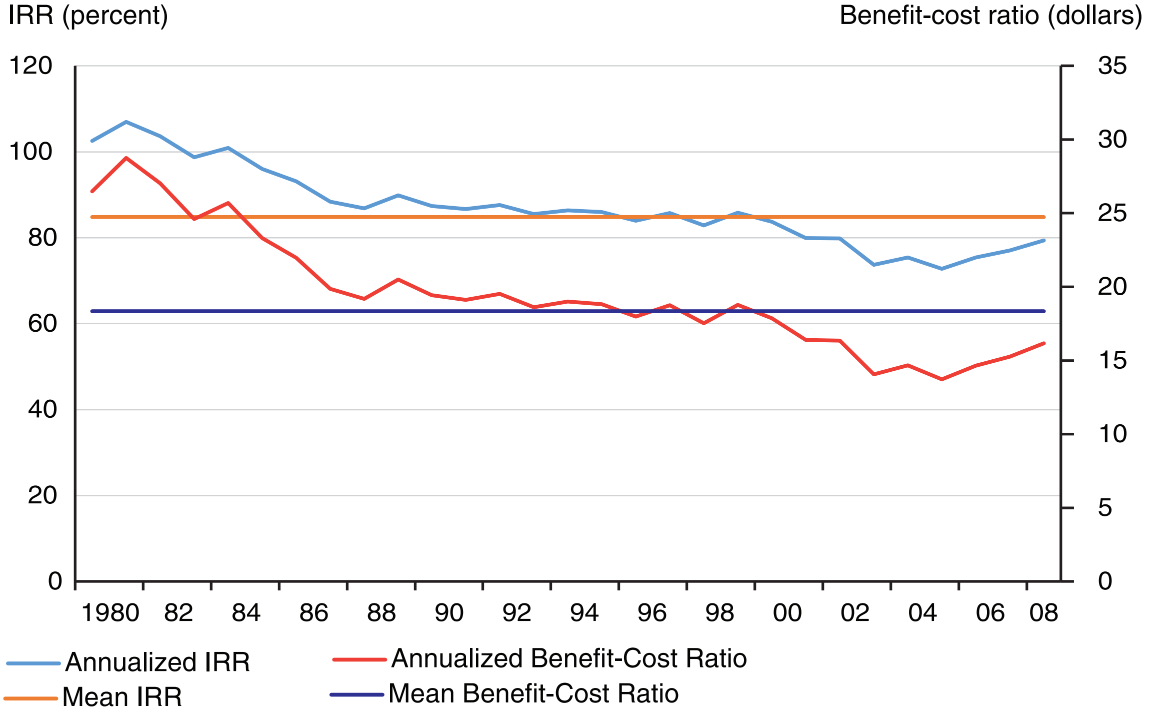
Returns to Public National Agricultural Research and Education Investments

Drawing on the national public agricultural research-TFP elasticity of 0.15 estimated in model specification (5) in table 2 and the time-varying impact of research investments given by (Appendix, Eq. 2), we estimate the benefits from an initial $1 increase in public agricultural research investment. From this analysis, we derive the internal rate of return (*irr*) and the benefit-cost ratio: India's internal rate of return was 85 percent and the benefit-cost ratio was 18.34.[17] Pal and Byerlee (2006) reviewed 10 Indian "aggregate" agricultural studies and calculated a mean *irr* of 75.4 percent, very close to our own finding.

Beyond these mean estimates, we investigate how these measures shifted over time. Evaluating the *irr* and benefit-cost ratio for each year between 1980 and 2008 reveals that the mean *irr* and benefit-cost ratio estimates conceal a long-term declining trend (fig. 18). Both decreasing trends, though, were a result of the constant research-TFP elasticity employed to compute the measures and the greater rate of growth of India's public agricultural research spending stock relative to output. Although the mean *irr* and benefit-cost ratios were sufficiently large to warrant greater investment in the sector, more research is required to determine if India's research-TFP elasticity has varied over time.

Figure 18

Declining internal rate of return and benefit-cost ratio trends



Notes: IRR = internal rate of return.
Source: Economic Research Service estimates.

---

[17] The reader is directed to the Appendix for technical details. In a review of 599 benefit-cost-ratio studies that reported the discount rate, Hurley et al. (2014) find the average, minimum, and maximum discount rates are 7.2 percent, 2.0 percent, and 15.0 percent per year, respectively. In calculating our benefit-cost ratio, we account for a developing country's higher opportunity cost of capital and assume a 10-percent real discount rate. This is higher than the 3 percent assumed for the United States (Alston et al., 2011), but in line with the 12 percent assumed for developing countries in Gittinger (1982).

Conclusion

Over 1980-2008, the Indian agricultural sector's total factor productivity (TFP) growth progressed at 2 percent annually. TFP growth was faster in those regions that complemented grain and specialty crop production with horticultural and animal products (West, South, and East India), slower in regions specializing in grains and animal products (North India), and also slower in regions unable to benefit from the higher returns from high-value commodity production (Central and Northeast India).

Regardless of India's output mix over time and across regions, public investment in the country's ICAR-SAU agricultural research system has been a primary mechanism for stimulating agriculture's long-term TFP growth. That effect has been greatest in the Northern, Western, and Central States. From 1980-2008, national public research spending generated an internal rate of return of 85 percent, or about \$18.34 in benefits for every \$1 spent on research. However, despite these high returns, benefits from the Indian public research system may have diminished since 1980. The number of FTE scientists working at SAU institutions has declined, as has the share of total public research funds allocated to the ICAR/SAU system. It is thus unclear whether the SAU institutional reforms and subsequent scientific labor release from the public research system will allow spending to shift to new research priorities.

Of further concern has been India's agricultural research intensity ratio, which rose slowly between 2000 and 2008, from 0.36 to 0.40 (Pal et al., 2012).[18] The 2008 value is smaller than the public research intensity ratio for that year from China (0.50) and well below the ratios of Brazil (1.80) and more developed economies, including South Korea (2.30), Australia (3.56), and Japan (4.75). Keeping pace with the world's agricultural technology leaders has become more important as many technologies generated in developed countries increasingly cannot be directly adopted or easily adapted by developing countries (Alston et al., 2006b).

Other factors affecting India's agricultural TFP growth include the following:

- ⊙ *Irrigation infrastructure.* Expansion of irrigated area has been the second most important mechanism for accelerating TFP. Much like the patterns of agricultural research, benefits from extending irrigation infrastructure have been greater for North and West India than for the rest of the country. We further found that the rapid growth in groundwater irrigation spurred TFP more than did surface-water irrigation. Access to well water greatly expanded arable land through double cropping and thus boosted productive capacity. Yet, excessive groundwater extraction has raised concerns of severe groundwater depletion in the hard-rock areas of peninsular India and parts of the arid alluvial plains in Northwest India (Akermann, 2012).

- ⊙ *Public investment in international agricultural research (through CGIAR).* Because public research spending by CGIAR specific to Asia was low between 2002 and 2010, India's agricultural research service and Indian agriculture as a whole can probably expect declining CGIAR contributions from that period. However, public investment did increase in 2011, rebounding to

---

[18] An agricultural research intensity ratio is defined as research spending per agricultural gross domestic product (Ag GDP). The measure allows for international comparison of a country's investment in its research system by accounting for relative sectoral size.

2002 levels, and has since continued to increase. Still, those years of declining investments will likely affect the Indian research system for years to come.

- *Private research.* We could not include private research directly into our econometric specification because of a lack of data. However, results from its proxy in our calculations—along with evidence of recent increased investment in seeds, machinery capital, and pesticides—show that private research is contributing to agricultural TFP growth.
- *Rural public education.* Given our findings that higher levels of rural education correlate with higher rates of technology adoption, India's persistent low levels of rural education suggest that lagging investment in rural education hampers implementation of agricultural innovations.

In sum, new growth in horticulture and animal products appears to be spurring India's TFP, especially in Western and Southern States. Yet despite these new sources of growth, agricultural research and irrigation infrastructure investments have continued to be the primary policy instruments propelling long-term TFP, especially in the North and West. Both policy tools could be useful as part of the National Food Security Mission, which since 2007, has introduced improved wheat and rice varieties and cultivation and water-use practices to the infrastructure-poor but water-rich Indian East.

References

Akermann, R. 2012. “New Directions for Water Management in Indian Agriculture,” *Global Journal of Emerging Market Economies* 4(2):227-288.

Alston, J., M. Anderson, J. James, and P. Pardey. 2010. *Persistence Pays: U.S. Agricultural Productivity Growth and the Benefits from Public R&D Spending*. New York, NY: Springer.

Alston, J., M. Anderson, J. James, and P. Pardey. 2011. “The Economic Returns to U.S. Public Agricultural Research,” *American Journal of Agricultural Economics* 93(5):1257-1277.

Alston, J., S. Dehmer, and P. Pardey. 2006a. “International Initiatives in Agricultural R&D: The Changing Fortunes of the CGIAR,” in *Agricultural R&D in the Developing World: Too Little Too Late?* Pardey, P., J. Alston, and R. Piggott eds., Washington, DC: International Food Policy Research Institute (IFPRI).

Alston, J., G. Norton, and P. Pardey. 1995. *Science under Scarcity: Principles and Practice for Agricultural Research Evaluation and Priority Setting*. Ithaca, NY: Cornell University Press.

Alston, J., P. Pardey, and P. Piggott. 2006b. “Synthesis of Themes and Policy Issues,” in *Agricultural R&D in the Developing World: Too Little Too Late?* Pardey, P., J. Alston, and R. Piggott eds. Washington, DC: International Food Policy Research Institute (IFPRI).

Amarasinghe, U., K. Palanisami, O. Singh, and R. Sakthivadivel, 2009. “State of Irrigation in Tamil Nadu: Investments and Returns," in *International Water Management Institute (IWMI). Strategic Analyses of the National River Linking Project (NRLP) of India Series 5*. Proceedings of the Second National Workshop on Strategic Issues in Indian Irrigation, New Delhi, India, April 8-9, 2009. Colombo, Sri Lanka: International Water Management Institute (IWMI). pp.53-81.

Anand, G. February 22, 2010. “Green Revolution in India Wilts as Subsidies Backfire.” *The Wall Street Journal*. http://online.wsj.com/articles/SB10001424052748703615904575052921612723844.

Azam, M. 2012. “The Impact of Indian Job Guarantee Scheme on Labor Market Outcomes: Evidence from a Natural Experience,” Discussion Paper No. 6548, Institute for the Study of Labor (IZA).

Beintema, N., P. Adhiguru, P. Birthal, and A. Bawa. 2008. “Public Agricultural Research Investments: India in a Global Context,” Policy Brief 27, National Centre for Agricultural Economics and Policy Research (NCAP), New Delhi, India.

Birthal, P., P. Joshi, S. Chauhan, and H. Singh, 2008. “Can Horticulture Revitalise Agricultural Growth?” *Indian Journal of Agricultural Economics* 63(3):308-321.

Bloomberg. 2015. Bloomberg Business, Company Snapshots. http://www.bloomberg.com/research/stocks/private/snapshot.asp?privcapId=61015499 (accessed April 2015).

Calderón, C., and L. Servén, 2004. “The Effects of Infrastructure Development on Growth and Income Distribution,” World Bank Policy Research Working Paper 3400, World Bank, Washington, DC.

CGIAR. Various annual reports. *CGIAR Financial Report.* Consultative Group for International Agricultural Research (CGIAR), Washington, DC.

Chand, R., P. Kumar, and S. Kumar. 2011. “Total Factor Productivity and Contribution of Research Investment to Agricultural Growth in India,” Policy Paper 25, National Centre for Agricultural Economics and Policy Research (NCAP), New Delhi, India.

CIMMYT. 2010. “India and CIMMYT: Highlights of a Longstanding Partnership for Agricultural Development.” International Maize and Wheat Improvement Center (CIMMYT), Mexico.

Easter, W., M. Abel, and G. Norton. 1977. “Regional Differences in Agricultural Productivity in Selected Areas of India,” *American Journal of Agricultural Economics* 59(2):257-265.

ERS. 2014. “International Macroeconomic Dataset,” U.S. Department of Agriculture, Economic Research Service (ERS), Washington, DC. http://www.ers.usda.gov/data-products/international-macroeconomic-data-set.aspx (accessed April 2014).

Evenson, R., C. Pray, and M. Rosegrant. 1999. “Agricultural Research and Productivity Growth in India,” International Food Policy Research Institute (IFPRI) Research Report 119, Washington, D.C. Data were compiled by A. Sanghi, K. Kumar, and W. McKinsey, Jr. http://ipl.econ.duke.edu/dthomas/dev_data/datafiles/india_agric_climate.htm.

Fan, S., P. Hazell, and S. Thorat. 1999. *Linkages between Government Spending, Growth, and Poverty in Rural India,* IFPRI Report 110, International Food Policy Research, Washington, D.C.

FAO. 2012. FAOSTAT Agricultural Databases. United Nations, Food and Agricultural Organization (FAO), Rome. http://faostat.fao.org/ (accessed March 2012).

FAO. 2014. FAOSTAT Agricultural Databases. United Nations, Food and Agricultural Organization (FAO), Rome. http://faostat.fao.org/ (accessed November 2014).

FAS. 2012. Production, Supply, and Distribution database. U.S. Department of Agriculture, Foreign Agricultural Service (FAS).

FAS. 2015. Production, Supply, and Distribution database. U.S. Department of Agriculture, Foreign Agricultural Service (FAS). http://www.fas.usda.gov/psdonline/psdHome.aspx (accessed January 2015).

Fuglie, K., and N. Rada. 2013. *Resources, Policies, and Agricultural Productivity in Sub-Saharan Africa*, ERR-145, U.S. Department of Agriculture, Economic Research Service.

GHI. 2014. Global Revolutions in Agriculture: The Challenge and Promise of 2050. 2014 Global Agricultural Productivity Report, Global Harvest Initiative (GHI). http://www.globalharvestinitiative.org/index.php/gap-report-gap-index/2014-gap-report/ Accessed on October 22, 2014.

Gittinger, J. 1982. *Economic Analysis of Agricultural Projects.* Baltimore, MD: Johns Hopkins University Press.

GOI. 2009. Agricultural Wages in India, various reports. Department of Agriculture & Cooperation, Ministry of Agriculture, Government of India (GOI).

GOI. 2010. Rural Labour Enquiry, Report on Wages & Earnings of Rural Labour Households. Government of India (GOI), Ministry of Labour and Employment, Labour Bureau.

GOI. 2015. Economic Survey 2014-15. Volume I. Department of Economic Affairs, Ministry of Finance, Government of India (GOI).

Gulati, A., T. Shah, and G. Shreedhar. 2009. *Agriculture Performance in Gujarat Since 2000: Can It Be a Divadandi (Lighthouse) for Other States?* International Water Management Institute (IWMI), Sri Lanka, and International Food Policy Research Institute (IFPRI), Washington, DC.

Hayami, Y., and V. Ruttan, 1985. *Agricultural Development*. Baltimore, MD: Johns Hopkins University Press.

Hendry, D., and J.F. Richard. 1982. "On the Formulation of Empirical Models in Dynamic Econometrics," *Journal of Econometrics* 20(1):3-33.

Huffman, W. November 2009. "Measuring Public Agricultural Research Capital and Its Contribution to State Agricultural Productivity." Working Paper No. 09022, Iowa State University, Department of Economics, Ames, IA.

Huffman, W., and R. Evenson. 1992. "Contributions of Public and Private Science and Technology to U.S. Agricultural Productivity," *American Journal of Agricultural Economics* 74(3):751-756.

Hurley, T., X. Rao, and P. Pardey. 2014. "Re-Examining the Reported Rates of Return to Food and Agricultural Resarch and Development," *American Journal of Agricultural Economics,* doi: 10.1093/ajae/aau047.

IITM. 2011. Government of India, The Indian Institute of Tropical Meteorology (IITM), Ministry of Earth Sciences http://www.tropmet.res.in/static_page.php?page_id=52 (accessed December, 2011).

Joshi, P., S. Pal, P. Birthal, and M. Bantilan. 2005. *Impact of Agricultural Research: Post Green Revolution Evidence from India*. National Centre for Agricultural Economics and Policy Research (NCAP), New Delhi, India, and International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India.

Kumar, P. A. Kumar, and S. Mittal. 2004. "Total Factor Productivity of Crop Sector in the Indo-Gangetic Plain of India: Sustainability Issues Revisited." *Indian Economic Review* 39(1):169-201.

Kumar, P., M. Gautum, and P. Joshi. 2013. "Total Factor Productivity Growth: A State Level Analysis." Background paper for "Republic of India: Accelerating Agricultural Productivity Growth." World Bank, Washington, DC.

Mahajan, K., and B. Ramaswami. 2012. "Caste, Female Labor Supply, and the Gender Wage Gap in India: Boserup Revisted." Conference paper for the 7th Institute for the Study of Labor (IZA)/ World Bank Conference: Employment and Development, November 4-6, 2012, New Delhi, India.

http://www.iza.org/conference_files/worldb2012/viewProgram?conf_id=2248. Accessed on January 1, 2013.

Mehta, R., R Nambiar, C. Delgado, S. Subramanyam. 2003. "Annex II: Livestock Industrialization, Project Phase II – Policy, Technical, and Environmental Determinants and Implications of the Scaling-up of Broiler and Egg Production in India" in *Policy, Technical, and Environmental Determinants and Implications of the Scaling-Up of Livestock Production in Four Fast-Growing Developing Countries: A Synthesis*, C. Delgado, C. Narrod, and M. Tiongco eds. Rome, Italy: United Nations, Food and Agriculture Organization. http://www.fao.org/WAIRDOCS/LEAD/X6170E/x6170e00.htm. Accessed on September 17, 2012.

Mullen, K., D. Orden, and A. Gulati. 2005. "Agricultural Policies in India: Producer Support Estimates 1985-2002," IFPRI Discussion Paper 82, International Food Policy Research Institute, Markets, Trade, and Institutions Division, Washington, DC.

Oehmke, J., and D. Schimmelpfennig. 2004. "Quantifying Structural Change in U.S. Agriculture: The Case of Research and Productivity," *Journal of Productivity Analysis* 21:297-315.

Pal, S., 2014. Personal Communication.

Pal, S., and D. Byerlee. 2006. "India: The Funding and Organization of Agricultural R&D – Evolution and Emerging Policy Issues," in *Agricultural R&D in the Developing World: Too Little Too Late?* Pardey, P., J. Alston, and R. Piggott, eds. Washington, DC: International Food Policy Research Institute (IFPRI).

Pal, S., M. Rahija, and N. Beintema. 2012. "India: Recent Developments in Agricultural Research," Agricultural Science and Technology Indicator (ASTI) Country Note. International Food Policy Research Institute (IFPRI), Washington, DC.

Pal, S., and A. Singh. 1997. "Agricultural Research and Extension in India: Institutional Structure and Investments," Policy Paper 7, National Centre for Agricultural Economics and Policy Research, New Delhi, India.

Pingali, P. 2006. "Agricultural Growth and Economic Development: A View Through the Global Lens." Presidential address to the 26th International Conference of Agricultural Economists (IAAE). Gold Coast, Australia. August 12-18, 2006.

Pray, C., and K.O. Fuglie. 2001. *Private Investment in Agricultural Research and International Technology Transfer in India*, AER-805, U.S. Department of Agriculture, Economic Research Service. http://www.ers.usda.gov/publications/aer-agricultural-economic-report/aer805.aspx

Pray, C., and L. Nagarajan. 2013. "Role of Biotechnology in Stimulating Agribusiness R&D Investment in India" *AgBioForum* 16(2):104-111.

Pray, C., and L. Nagarajan. 2014. "The Transformation of the Indian Agricultural Input Industry: Has it Increased Agricultural R&D?" *Agricultural Economics* 45:145-156.

Rabobank. 2012. "Indian Buffalo Meat," Rabobank Industry Note 344, Rabobank International Food and Agribusiness Research and Advisory, Netherlands.

Rada, N. 2013. “Agricultural Growth in India: Examining the Post-Green Revolution Transition.” Selected Paper prepared for the 2013 Agricultural and Applied Economics Association Annual Meeting, Washington, DC, August 4-6.

Rada, N., and K. Fuglie. 2012. “Shifting Sources of Agricultural Growth in Indonesia,” in *Productivity Growth in Agriculture: An International Perspective*, K. Fuglie, S.L. Wang, and V.E. Ball, eds. United Kingdom: CAB International.

Rangarajan, C., P. Kaul, and Seema. 2011. “Where is the Missing Labour Force?” *Economic and Political Weekly* 46(39):68-72.

Rosegrant, M., and R. Evenson. 1992. “Agricultural Productivity and Sources of Growth in South Asia,” *American Journal of Agricultural Economics* 74(3):757-761.

Shankar, V., H. Kulkarni, and S. Krishnan. 2011. “India’s Groundwater Challenge and the Way Forward,” *Economic and Political Weekly* 46(2):37-45.

Shreedhar, G., N. Gupta, H. Pullabhotla, A. Ganesh-Kumar, and A. Gulati. 2012. “A Review of Input and Output Policies for Cereals Production in India,” International Food Policy Research Institute (IFPRI) Discussion Paper 01159. New Delhi, India.

Sims, H. 1993. “Economic Imperatives, Political Risks, and Modes of Action: Agricultural Policy Implementation in India and Pakistan,” *The Journal of Developing Areas* (27)2:145-162.

Singh, A., and S. Pal. 2010. “The Changing Pattern and Sources of Agricultural Growth in India” in *The Shifting Patterns of Agricultural Production and Productivity Worldwide*. Ames, Iowa: Iowa State University, the Midwest Agribusiness Trade Research and Information Center.

Ward, P., D. Ortega, D. Spielman, and V. Singh. 2014. “Heterogeneous Demand for Drought-Tolerant Rice: Evidence from Bihar, India,” *World Development* 64:125-139.

World Bank, 2012. World Development Indicators On-Line. World Bank, Washington, DC. http://www.worldbank.org/ (accessed December 2012).

World Bank. 2014a. World Development Indicators On-Line. World Bank, Washington, DC. http://www.worldbank.org/ (accessed April 2014).

World Bank. 2014b. *Republic of India: Accelerating Agricultural Productivity Growth*, World Bank Report 88093-IN, Washington, DC.

Appendix: A Review of Technical Details, Variables, and Method for Measuring Total Factor Productivity

Technical details of the production data and estimation procedures are provided here. Prior to defining the policy variables and models for explaining total factor productivity (TFP) growth and estimating India's return to public agricultural research, we first define the variables used to construct TFP and the method for measuring it.

Total Factor Productivity Data

Sources of agricultural production data are described in Appendix table 1. Regional production reflects data from the 16 States, but national production reflects data from all Indian States. All output and input data are recorded in metric tons. Farm-gate prices for all commodities are reported in rupees per quintal.[19] All prices and values are converted to 2004 constant rupees using the World Bank's gross domestic product (GDP) deflator specific to India (WDI, 2014).

Output

The 59 crop and 4 livestock commodities for which data are available are aggregated into a single chain-weighted Tornqvist-Theil quantity index. Missing national data were interpolated using United Nations, Food and Agriculture Organization (FAO) growth rates; missing State data were interpolated using national growth rates. Only three commodities assume national FAO quantities: (1) melons, (2) mangoes and guavas, and (3) pears and quince. They were included because the data exist at the State level, even though they represent a small fraction of the value of commodities.

Indian meat production data are recorded by the Ministry of Agriculture's Department of Animal Husbandry, Dairying, and Fisheries. These data are available only since 1992 and are reported as an aggregate; individual animal production statistics do not begin until 1998. Meat values, collected by the Central Statistical Organization's Department of Statistics, are available since 1990. A comparison of Government of India (GOI) aggregate national meat production volumes with FAO (2012) and USDA (2012) meat volumes provide little confidence in the Indian data (Appendix fig. 1). In particular, we note the significant jump in GOI meat volumes after 2005 depicted in Appendix figure 1. This jump reflects a change in the poultry data collection process (Mehta et al., 2003). For example, Haryana, Maharashtra, Orissa, Punjab, Tamil Nadu, and Old Uttar Pradesh showed substantial production changes between 2005 and 2007, roughly tripling national poultry production volumes from 537 thousand tons to 1.78 million tons. Notably, by 2007, GOI-recorded poultry volumes matched FAO poultry volume data.

Estimates of total meat values are, however, very similar to those reported by FAO (Appendix fig. 2). We, therefore, estimate a new meat volume series based on an FAO national meat price—averaged across buffaloes, cattle, goat and sheep, and poultry—and Indian national and State meat values. The FAO average national meat price is derived from FAO average meat values and volumes. Unfortunately, FAO meat values between 1980 and 1990 are unavailable. We extend the cattle and buffalo meat values back from 1990 to 1980 by applying the growth rate from the product of FAO-reported volumes and border (export) prices; while goat, sheep, and poultry FAO meat values are extended back by applying growth from the consumer price index specific to India (World Bank, 2012).

---

[19] 1 quintal = 100 kilograms.

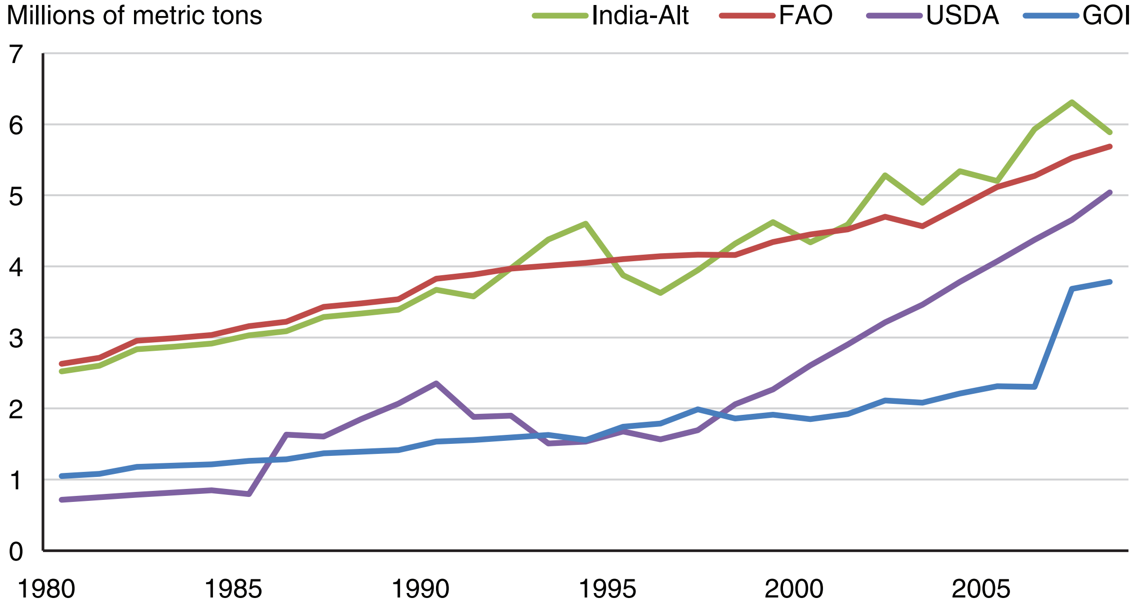
Appendix table 1

Agricultural production and policy data sources

Series	Level of aggregation	Source
Crop production	State	Government of India, Ministry of Agriculture and Farmers Welfare, Department of Agriculture and Cooperation, Directorate of Economics and Statistics, Agricultural Statistics at a Glance (1980-2009)
Wool production	State	Indiastat.com, accessed in 2010-11, Datanet India Pvt. Ltd., New Delhi, India
Eggs production	State	Government of India, Ministry of Agriculture, Directorate of Economics and Statistics, Bulletin on Food Statistics (1980-1995)
Milk production	State	Government of India, Ministry of Agriculture, Department of Animal Husbandry and Dairying and Fisheries, Basic Animal Husbandry Statistics (1999, 2006, 2008, 2010)
Meat production	State	Government of India, Central Statistical Organization, Department of Statistics Food and Agricultural Organization (FAOSTAT)
Farm animals in stock	State	Government of India, Ministry of Agriculture, Department of Animal Husbandry and Dairying and Fisheries, Livestock Census Report (1982, 1987, 1992, 1997, 2003, 2007)
Farm level commodity prices	State	Government of India, Ministry of Agriculture, Department of Agriculture and Co-operation, Directorate of Economics and Statistics, Agricultural Statistics at a Glance (1980-2009) Government of India, Ministry of Agriculture, Department of Agriculture and Co-operation, Directorate of Economics and Statistics, Farm harvest prices of principal crops in India (2004-2009)
Farm wages	State	Government of India, Ministry of Agriculture, Department of Agriculture and Co-operation, Agricultural Wages in India (1980-2009)
Agricultural land use	State	Government of India, Ministry of Agriculture, Department of Agriculture and Co-operation, Directorate of Economics and Statistics, Agricultural Statistics at a Glance Government of India, Ministry of Agriculture, Department of Agriculture and Co-operation, Directorate of Economics and Statistics, Land Use Statistics at a Glance (1996-97; 2005-06)
Farm labor	State	Government of India, Ministry of Statistics & Program Implementation, National Sample Survey Office, National Statistical Organization, NSS-ROUNDS (43rd round, 1987, 50th round, 1993-94, 55th round, 1999-00, 61st round, 2004-05, 66th round, 2009-10) Fan et al. (1999) for survey years (1977-78; 1983-84; 1993-94)
Fertilizer use	State	Indian Harvest, Accessed in 2010-11, Centre for Monitoring Indian Economy Pvt. Ltd., Mumbai, India
Fertilizer prices	State	Fertilizer Statistics (1980-2009), The Fertilizer Association of India, New Delhi. India
Electricity consumption	State	http://www.epwrfits.in/index.aspx, accessed in November 2011, India Time Series data. Economic and Political Weekly Research foundation, Mumbai, India
Electricity tariffs	State	All India Electricity Statistics—A General Review (1995-2009), Central Electricity Authority, Ministry of Power, Government of India
Animal stock service prices	National	Food and Agricultural Organization (FAOSTAT)
Agricultural tractors in use	State	Agricultural Research Data Book (2004-2010), Indian Agricultural Statistics Research Institute (Indian Council of Agricultural Research (ICAR)), New Delhi, India
Agricultural tractor rental rates	National	Evenson et al. (1999) and the Food and Agricultural Organization (FAOSTAT)

Appendix figure 1

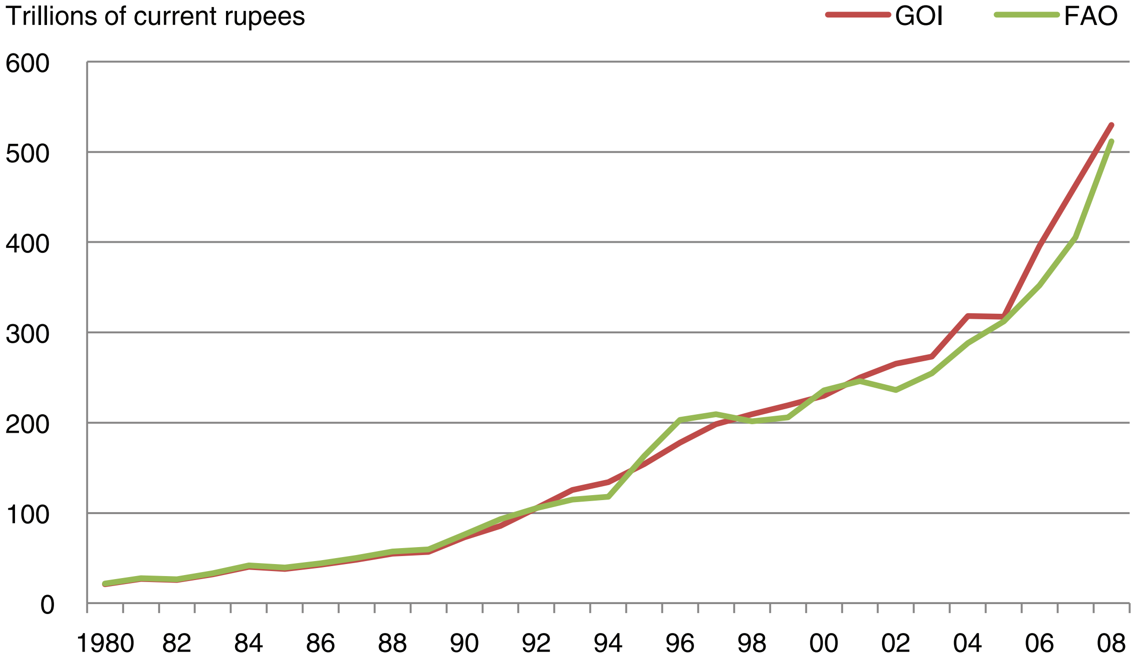
Comparing meat production volumes



Note: Government of India (GOI) meat volumes include buffalo, cattle, goat, sheep, pig, and poultry meat. Food and Agriculture Organization (FAO, 2012) meat volumes include buffalo, cattle, goat, sheep, pig, chicken, and duck meat. USDA, Foreign Agricultural Service (FAS, 2012) meat volumes include buffalo and cattle meat, pig meat, and poultry meat. The India-Alt variable is derived from GOI State meat values and FAO national meat prices.
Source: USDA, Economic Research Service estimates.

Appendix figure 2

Comparing meat production values



Note: Government of India (GOI, 2012) meat values include buffalo, cattle, goat, sheep, pig, and poultry meat. Food and Agriculture Organization (FAO, 2012) meat values include buffalo, cattle, goat, sheep, pig, chicken, and duck meat.
Source: USDA, Economic Research Service estimates.

Labor Inputs

Labor inputs consist of rural and urban adult male and female laborers employed in the agricultural sector. These data are obtained from the 43rd (1987-88), 50th (1993-94), 55th (1999-00), 61st (2004-05), and 66th (2009-10) rounds of the National Sample Survey (NSS). Because the earliest State-level labor counts available are from survey year 1987, State-specific growth rates were employed, following careful consideration of State-wise and time-wise variations, from Fan et al. (1999) to extend our State labor counts back to 1980. Fan et al. provide agricultural employment from the NSS by Indian State and nationally for survey years 1972, 1977, 1983, 1987, and 1993. Survey years 1977 and 1983 enable our labor data to be extended back from 1987, and years 1987 and 1993 enable State-wise and time-wise labor validation. We generate continuous a time series of labor counts through linear interpolation of survey years.

Drawing on a fixed number of days worked per year by male farm laborers, available by Indian State from Evenson et al. (1999), we develop an annual flow of labor inputs. Weighting these State labor-days worked by each State's respective share of total labor indicates that males, at the national level, work 227 days per year. India's Ministry of Labour and Employment reports that male (female) waged agricultural laborers worked 227 days per year in 1977-78, falling to 215 days worked per year in 2004-05, and female waged agricultural laborers worked 182 days per year in 1977-78, falling to 177 days worked per year in 2004-05 (GOI, 2010). Evenson et al.'s (1999) State variation in male days worked in 1978 serves as our base, from which we apply the Ministry of Labor and Employment's national average annual growth rate of days worked per year to obtain annual and State-wise variation in male labor-days worked between 1980 and 2008. The annual number of female labor-days worked by Indian State is unknown. We, therefore, assign to each State the national estimate.

Wages for male laborers are reported as rupees per day and are available annually by State. The national wage rate for each year is computed as a labor-quantity weighted average of State wages. Labor wages are simple averages across all operations (plowing, sowing, reaping, harvesting, weeding, and transplanting). Female wages are unavailable for most years and States. We employ the female-to-male labor wage ratios estimated by Mahajan and Ramaswami (2012) to obtain female wage rates. Female-to-male wage ratios for Himachal Pradesh are not available. We thus assign to Himachal Pradesh the average ratio of neighbor States Haryana, Punjab, and Old Uttar Pradesh.

Intermediate Inputs

Intermediate inputs consist of synthetic crop fertilizers and electricity consumed in the agricultural sector and are recorded annually. Nitrogen, phosphate, and potash use is recorded in metric tons of active ingredient. Fertilizer prices are recorded in rupees per metric ton of urea, diammonium phosphate (DAP), and muriate of potash (MOP). These prices are converted to rupees per ton of active ingredient, assuming urea is 46 percent nitrogen, DAP is 18 percent nitrogen and 46 percent phosphate, and MOP is 60 percent potassium. Fertilizer prices are regulated at the national level, although some State-wise variation of fertilizer prices exists due to State and local taxes. Electricity consumption is recorded as kilowatt hours (kwh) per capita. State electricity use is estimated as per-capita consumption weighted by State population. Electricity tariffs, specific to agriculture, are recorded as rupees per kwh and are available from 1991 to 2008. Agricultural electricity tariff rates for 1980-1990 assume the general electricity tariff growth rate for those years.

Capital Inputs

Between 1980 and 2003, agricultural tractors-in-use rose by an average annual 9.5 percent. Official statistics, however, suggest no tractor growth between 2003 and 2008 at the national level despite growth recorded at the State levels. Thus, for each year over 2004-2008 at the national level, we apply the annual growth rate of the sum of State tractors-in-use. This adjustment suggests India's average annual growth rate of machinery rose 7.23 percent between 2003 and 2008.

Tractor service prices are from Evenson et al. (1999) and FAO. Evenson et al. note that tractor prices are invariant across Indian States and thus estimate a single national rate from 1957 to 1987. That rate represents the price of an Eicher 24-horsepower tractor, adjusted upward to reflect the market share of machinery of higher horsepower, and deflated by 25 percent to account for depreciation and debt services. To extend this rate forward from 1987 to 2008, we assume the growth rate of the border (export) price of an FAO agricultural tractor specific to India, converted from dollars to rupees using World Bank (2012) conversion factors, and similarly depreciated.

In constructing the livestock capital input's expenditure share, we find that a historical cattle sale price series, based on domestic or border (export) information, is unavailable from Indian sources. Neither is one available from FAO: Indian cattle export data stop after 1995 and resume only sparsely after 2002. We, therefore, employ the Asian regional cattle export price, deflated by 15 percent to account for depreciation and any debt services, as our livestock capital service price.

Total Factor Productivity Measurement

We measure India's agricultural TFP growth using a chain-weighted Tornqvist-Theil quantity index. The chain-weighted Tornqvist-Theil TFP growth index may be expressed as

$$\text{(Eq. 1)} \quad \ln\left(\frac{TFP_{i,t}}{TFP_{i,t-1}}\right) = \left[\sum_j \frac{\left(R_{ij,t} + R_{ij,t-1}\right)}{2} \ln\left(\frac{Y_{ij,t}}{Y_{ij,t-1}}\right)\right] - \left[\sum_l \frac{\left(C_{il,t} + C_{il,t-1}\right)}{2} \ln\left(\frac{X_{il,t}}{X_{il,t-1}}\right)\right]$$

where i indicates the State, regional, and national production panels, $i = 1, 2, \ldots, 23$; j indicates the commodities included, $j = 1, 2, \ldots, 64$; l indicates the factors of production, $l = 1, 2, \ldots, 6$; t indicates time, $t = 1980, 1981, \ldots, 2008$; R is the revenue share; Y is output; C is the cost share, and X is input. Equation (1) expresses aggregate TFP growth of observation i, between time periods t and $t\text{-}1$, as the difference between aggregate output growth and aggregate input growth. Aggregate output growth is defined as the sum of all commodity output growth rates, and each growth rate weighted by its respective average revenue share in the reference time periods. Input growth is defined as the sum of all factor input growth rates, and each growth rate weighted by its respective average cost share in the reference time periods.

Policy Variables Hypothesized To Propel Agricultural TFP

Beyond the policy variables of interest detailed in the text, the model controls for variations in rainfall across Indian States. Average annual rainfall estimates are available from the Indian Institute of Tropical Meteorology (IITM).

India's Public National Agricultural Research and Education

Public agricultural research and education investments, between 1960 and 1994, are available for each State Agricultural University (SAU) and the Central Government from Pal and Singh (1997). Research investments from 1995 to 2003 are available from the Indian Government's Planning Commission report on the Finances of State Governments in India, and from 2004 to 2008, from the Reserve Bank of India's Annual Report of State finances. SAU research expenditures are specific to each State. Because Central funds allocated to agricultural research are administered by the Indian Council of Agricultural Research (ICAR) and are used for research over a national scope, we apply the ICAR research funds to each SAU when constructing State research stocks. All research expenditures are normalized to 2004 constant rupees by the World Bank's GDP deflator specific to India.

International Public Agricultural Research

International agricultural research is modeled using expenditures by the CGIAR for Asia. Research expenditures are drawn from annual financial reports, and the share allocated to Asia was first reported in 1984 at 25 percent. After 1984, Asia's share of global CGIAR research expenditures are available in years 1990, 1995, 2000, and then annually after 2002. Unavailable years between 1984 and 2001 are interpolated assuming linear growth. We extend the CGIAR's Asia research expenditures prior to 1984 by employing CGIAR research center-specific research expenditures available from Alston et al. (2006a). We assume 100 percent of research and technologies developed at the International Rice Research Institute (IRRI) and at the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) are directed toward Asia. We assume 50 percent of research and technologies developed at the International Maize and Wheat Improvement Center (CIMMYT) are directed toward Asia. Research expenditures from these three research centers are used to develop CGIAR research shares for Asia between 1960 and 1984. Because nearly all of the research conducted in the early 1960s is related to Green Revolution agricultural technologies, Asia's share of CGIAR research expenditures initially defines CGIAR's global research expenditures. As other research centers developed in the 1960s and 1970s, the share declined to roughly 30 percent by 1984 and has since maintained that share.

National and International Research Stock Estimation

We assume that the annual service flows from research spending that build up and die out can be added together to form a moving average of research effects on productivity. This stock of research can be estimated directly by assuming that the weights given to different annual contributions to the stock are constant but that the level of annual spending might vary from year to year. Converting these insights into empirical models that economize on required degrees of freedom has been somewhat contentious. If the entire build-up and die-down period for annual research spending is fairly short, the entire distribution might be estimated by a single annual lag. More realistically, a smoothly increasing and decreasing set of weights of various lengths can be parsimoniously estimated by a polynomial distributed lag (PDL) model, where the weights lie on a function made up of a constant and the research variable in its levels and power terms. If a single year is the extreme version of a "peak-effects" model, then the increasing and declining set of related lag weights represented by a narrow version of a PDL can provide a peak-effect model with realistic rising-then-falling lag weights.

A competing empirical model that also captures the aggregate effects of a time series of research spending is the trapezoidal model. These lag distributions have flat tops that better represent the aggregate impacts of research when annual spending climbs to a peak effect and stays at that level for some time. "Traps" avoid a problem that PDLs can have when estimating long lags. Because PDL weights are estimated to fit along a smooth function, the only way for a PDL to fit a function from the first peak effect to the last peak effect is to create a hump in the middle of the lag distribution. This hump may be caused by the need of the function to create a smooth series of weights rather than an actual characteristic of the data. We tested a series of traps to address this issue. The best traps had shorter build-up than die-out lags; one good performer was tested with a 2-year gestation lag, and one trap worked well that had a longer flat top and a much longer die-out of almost 20 years. Each of these three best performing traps was tested with both national and international research expenditures.

The trapezoidal formulations worked better than the PDLs, but since there were several different research series that needed to be tested together, a few single lags (with peak effects) were tested with the traps. Since none of these single lags worked well, very few tests were done that included both traps and PDLs, although PDLs were tested extensively on their own. The final models selected were chosen using the general-to-specific guidelines recommended by Hendry and Richard (1982): goodness of fit (variance dominance), data coherence (models yielding white-noise error processes), parameter parsimony, and consistency with theory, with about equal weight on each factor.

The estimated national (*NARE*) research stocks are weighted sums of current and previous years' research and education expenditures (RE_{it}):

$$
\begin{aligned}
\text{(Eq. 2)}\quad NARE_{it} = {} & 0.000\left(RE_{it}\right) + 0.000\left(RE_{i,t-1}\right) + 0.016\left(RE_{i,t-2}\right) + 0.032\left(RE_{i,t-3}\right) \\
& + 0.048\left(RE_{i,t-4}\right) + 0.063\left(RE_{i,t-5}\right) + 0.079\left(RE_{i,t-6}\right) + 0.095\left(RE_{i,t-7}\right) \\
& + \ldots + 0.095\left(RE_{i,t-10}\right) + 0.085\left(RE_{i,t-11}\right) + 0.074\left(RE_{i,t-12}\right) + 0.063\left(RE_{i,t-13}\right) \\
& + 0.053\left(RE_{i,t-14}\right) + 0.042\left(RE_{i,t-15}\right) + 0.032\left(RE_{i,t-16}\right) + 0.021\left(RE_{i,t-17}\right) \\
& + 0.016\left(RE_{i,t-18}\right) \\
= {} & \sum_{l=0}^{18} \gamma_l RE_{i,t-l}
\end{aligned}
$$

where $l=0,1,\ldots,18$, γ reflects the lag weights, and $\sum\gamma_1 = 1$. Similar to the *NARE* stock, the public international research stock (*CG_Asia*) is the weighted sum of current and previous years' research expenditures (*R*):

$$\text{(Eq. 3)}\quad \begin{aligned} CG\_Asia_{it} = {} & 0.007\left(R_{it}\right)+0.015\left(R_{i,t-1}\right)+0.022\left(R_{i,t-2}\right)+0.029\left(R_{i,t-3}\right) \\ & +0.037\left(R_{i,t-4}\right)+0.044\left(R_{i,t-5}\right)+0.051\left(R_{i,t-6}\right)+\ldots+0.051\left(R_{i,t-12}\right) \\ & +0.049\left(R_{i,t-13}\right)+0.046\left(R_{i,t-14}\right)+\ 0.044\left(R_{i,t-15}\right)+0.041\left(R_{i,t-16}\right) \\ & +0.039\left(R_{i,t-17}\right)+0.036\left(R_{i,t-18}\right)+0.033\left(R_{i,t-19}\right)+0.031\left(R_{i,t-20}\right) \\ & +0.028\left(R_{i,t-21}\right)+0.026\left(R_{i,t-22}\right)+0.023\left(R_{i,t-23}\right)+0.020\left(R_{i,t-24}\right) \\ & +0.018\left(R_{i,t-25}\right)+0.015\left(R_{i,t-26}\right)+0.013\left(R_{i,t-27}\right)+0.010\left(R_{i,t-28}\right) \\ & +0.008\left(R_{i,t-29}\right)+0.005\left(R_{i,t-30}\right)+0.003\left(R_{i,t-31}\right) \\ & =\sum_{l=0}^{31}\gamma_l R_{i,t-l} \end{aligned}$$

where $l=1,2,\ldots31$ and γ is, as in Equation (2), reflective of the lag. Thus, international investments in CGIAR research provide research benefits over a 31-year period.

Rural Road Infrastructure

Kilometers of rural roads are recorded annually for each Indian State and at the national level. These data were accessed from Indiastat.com, but drawn from Basic Road Statistics of India annual reports from the Ministry of Shipping, Road Transport and Highways, Government of India. These data are normalized by State area to create a road density variable (km of rural roads/km^2 land area).

Econometric Models

Our purpose is to investigate policies that have accelerated India's agricultural TFP growth since 1980. In doing so, we consider the TFP-growth effect of (1) national investments in public agricultural research and education ($NARE_{it}$), (2) international public agricultural research spill-ins sourcing from CGIAR research specific to Asia (CG_Asia_t), (3) public and private investment in irrigation capital ($Irrig_{dit}$), (4) rural road infrastructure ($Roads_{it}$), and (5) rural schooling specified in linear and quadratic forms ($Schooling_{it}$ *and* $Schooling_{it}^2$). We test our specifications by including a time trend (*t*) to monitor the robustness of our estimates to inclusion of a general time variable and a rainfall variable ($Rain_{it}$) to control for precipitation variations. A time trend is often used in empirical work to capture missing or unmeasured variables that incrementally rise with time. We are using this empirical regularity to test the effect of difficult-to-measure factors related to TFP, such as private-sector research.

Other variables with similar time trends could also be captured by the trend, as appears to be the case for international research as discussed in the text. Another common concern regarding the inclusion of research and development (R&D) stock variables is that they trend over time, and are thus capturing the same effect as would a more general time trend. This tends to serve as a robustness check for the R&D stock variables, because if they can be adequately modeled by a time trend, their explanatory power must be unacceptably low.

Our model is specified as:

$$\text{(Eq. 4)}\quad \begin{aligned}\ln\left(TFP_{it}\right) \;=\; & \alpha \;+\; \beta_1 \ln\left(NARE_{it}\right) \;+\; \beta_2 \ln\left(CG\_Asia_t\right) \;+\; \beta_3 \ln\left(Irrig_{dit}\right) \\ & + \beta_4 Schooling_{it} + \beta_5 Schooling_{it}^{\;2} + \beta_6 \ln\left(Roads_{it}\right) + \beta_7 Rain_{it} \\ & + \beta_8 t \;+\; \beta_9 \ln\left(NARE_{it}\right)^{*}\mathrm{Reg}_c + \beta_{10} \ln\left(Irrig_{it}\right)^{*}\mathrm{Reg}_c \\ & + \mu_i + \varepsilon_{it}\end{aligned}$$

where i represents 16 Indian States; *t* annually represents years 1980-2008; the sub-index *d* on ($Irrig_{dit}$) denotes either aggregate (total) irrigation, surface-water irrigation specific to an area irrigated by canals, or ground-water irrigation specific to an area irrigated by wells; Reg_c is a regional dummy variable, where c = North, South, West, East, Central, and Northeast; α is a State-common intercept term, μ_i is a State-random effects term, and ε_{it} is a random and independent econometric error term.[20] All variables included in Equation (6) are in log form except *Schooling*, *t*, and *Rain*. These are annual variables best interpreted without logs.

The public agricultural research estimated parameter value (β_1) in Equation (4) is an elasticity that indicates the proportionate change in TFP-growth, given a 1-percent increase in India's stock of public agricultural research expenditures, all else equal. That research elasticity, along with the time structure of research effect specified in Equation (2), allows for the estimation of India's public agricultural rate of return (Alston et al., 1995). Because TFP equals change in output when inputs are held fixed, the research-TFP elasticity is equivalent to the research-output elasticity. We specify the research-TFP elasticity (η) as

$$\text{(Eq 5)}\quad \eta = \frac{\partial \ln TFP}{\partial \ln S} = \frac{\partial \ln Y}{\partial \ln S} = \left(\frac{\partial Y}{\partial S}\right)\left(\frac{\overline{S}}{\overline{Y}}\right)$$

where *S* represents the stock of agricultural research, *Y* represents output, and the bars over *S* and *Y* reflect period averages. Isolating the marginal product of the research stock on the left-hand side gives

$$\text{(Eq 6)}\quad \frac{\partial Y}{\partial S} = \left(\frac{\overline{Y}}{\overline{S}}\right)\eta$$

We derive the *irr* by considering the effect of a one-time increase in research expenditure *R* on subsequent output. From Equation (2), we know that research spending in year t affects the research stock (and thus output) for 18 years; that is, at the national level, $NARS_t = \sum_{l=0}^{18} \gamma_l R_{t-l}$.

---

[20] The Breusch-Pagan Lagrangian Multiplier (LM) test is decisive that there are individual (State) effects (chibar2 (01) = 853.59; Prob > chibar2 =0.000). The Hausman test indicates the presence of systematic differences between the State-fixed and State-random effects models (chi2 (7) = 8.62; Prob > chi2 = 0.1961); thus the random effects model estimator is the better choice. The random effects model takes a weighted average of the fixed and between estimates and, as appears to be the case, allows for the possibility that State effects might vary over time.

Therefore, the stream of impacts on output from a change in research expenditures in time *t* is given by:

$$\text{(Eq 7)} \quad \frac{\partial Y}{\partial R_t} = \left(\frac{\partial Y}{\partial S}\right)\left(\frac{\partial S}{\partial R_t}\right) = \left(\frac{\overline{Y}}{\overline{\overline{S}}}\right)\eta\sum_{l=0}^{18}\gamma_l .$$

The above equation provides the changes in output from a one-time increase in research spending *R* at time *t* over the course of the 18 years in which research spending provides research benefits. The *irr* to research is the discount rate that equates the present value of costs ($1 expenditures on research in time *t*) to benefits (i.e., the change in output caused by this research over the current and subsequent 18 years):

$$\text{(Eq 8)} \quad 1 = \left(\frac{\overline{Y}}{\overline{\overline{S}}}\right)\eta\sum_{l=0}^{18}\frac{\gamma_l}{(1-irr)^l} .$$