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The growing role of the private sector in agricultural research and development world-wide

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ABSTRACT

The private sector is playing an important role in developing technologies to raise productivity in agriculture. This paper presents new estimates of private agricultural and food R&D spending trends over the past 25 years. Global private spending on agricultural R&D (excluding R&D by food industries) rose from $5.1billion in 1990 to $15.6billion by 2014. Private R&D investment accelerated as agricultural commodity prices began to rise in 2003. Although the companies that account for most agricultural R&D spending are based in developed countries, their technologies have considerable and growing importance for developing countries. Some implications of these trends for public R&D policy are discussed.

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1. Introduction

Raising investment in agricultural research and development (R&D) to raise productivity of the world's farms, especially in developing countries, is thought to be essential for long-term global food security (Alston et al., 2009; Lobell et al., 2013). Although historically (due to market failures and the small size of agricultural firms) the public sector led investment in agricultural R&D, private agribusiness is playing an increasingly important role (Fuglie et al., 2012). Recent estimates of global spending on food and agriculture R&D found that private R&D has grown faster than public R&D, and in developed countries private spending now exceeds that by the public sector (Bientema et al., 2012; Pardey et al., 2015a).

How relevant is this trend for raising agricultural productivity in developing countries? One limitation of many global assessments is that estimates for the private sector combine R&D spending on food manufacturing and agricultural inputs. But detailed studies have shown that R&D by food companies is heavily oriented toward improving manufacturing processes and developing new food products. Except in some vertically integrated sectors like poultry, food R&D has limited relevance for production agriculture (Conner, 1981; Galizzi and Venturini, 1996; Fuglie et al., 2011). More relevant for agriculture is R&D spending by agricultural input manufacturers – seed, chemical, pharmaceutical, and machinery companies that invest in R&D to improve the quality of farm inputs. In an assessment of agriculturally-related R&D by agribusinesses, Fuglie et al. (2011) estimated that private agricultural R&D world-wide nearly doubled between 1994 and 2010, from $5.6 billion to $11.0 billion per year. Although more than 95% of this R&D was by companies based in developed countries, many of these companies operated global research networks to adapt and extend their technologies to serve global markets.

This paper extends Fuglie et al.'s (2011) results on global private agricultural R&D[1] spending to cover the years from 1990 to 2014. Having more up-to-date data provides insights into how international agribusiness responded to the rise in commodity prices since 2007. Generally, we would expect higher commodity prices to lead to greater farm demand for yield-increasing technologies, and thus greater R&D spending by agricultural input manufacturers to meet this demand. However, given the long lead times between new R&D spending and technology development and adoption, we would except a strong R&D response only if the price increases were expected to persist rather than be cyclical.

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[1] Private agricultural R&D is defined as R&D by the business sector to develop new technologies for crop, livestock and aquaculture production. The business sector includes private and state-owned enterprises so long as they sell their products to the market. It excludes R&D by institutions financed by producer groups or industry associations as well as R&D by private universities.

The paper also revisits the question of how relevant private agricultural R&D might be for developing countries. Most private agricultural R&D is by companies located in high-income countries, although some of this is targeted to markets in developing countries. R&D spending by firms based in emerging economies is also growing. This paper uses two methods to allocate private agricultural R&D spending to markets in high income and developing countries. First, R&D spending is assumed to be targeted to the country or region in which each company is headquartered. Second, R&D is allocated to the country or region where each company sells its products. The second measure assigns a significantly larger share of private agricultural R&D to developing countries. The paper also examines how national policies in developing countries can incentivize private R&D, including by foreign multinational corporations, in their countries. Drawing on evidence from case studies presented in Pray and Fuglie (2015) and recent developments in agribusiness, the strategies pursued by the three largest emerging economies – China, India and Brazil - for acquiring agricultural technology services from the private sector are compared.

The paper concludes with a summary of key findings and discussion of their implications for science policy.

2. Methodology

For most countries, official estimates of private investment in agriculturally-related R&D are not comprehensive, if they exist at all. For countries that do report private agricultural R&D, it usually only covers R&D spending by firms in the farm sector (i.e., firms which primarily produce crop and livestock commodities). This misses most of the R&D by chemical, pharmaceutical, machinery, and biotechnology firms which develop and manufacture inputs for use by farms for agricultural production. This omission characterizes the private agricultural R&D data reported for European countries by the Eurostat and OECD databases. Only a few countries report private R&D spending by “socioeconomic objective,” i.e., by the sector of intended use. The U.S. National Science Foundation (NSF), for example, occasionally reports R&D spending by firms in the manufacturing and service sectors that is intended for agriculture, but excludes agricultural firms from its surveys. Thus, it misses R&D spending by crop seed and animal breeding companies (which are classified as agricultural because they sell agricultural seedstock, though they are not “farms” in the usual sense). Fuglie et al. (2011) found R&D by seed companies to be the largest and most rapidly expanding component of private agricultural R&D spending in the United States.

To remedy this gap Fuglie et al. (2011) constructed a new and unique dataset on private agricultural R&D spending world-wide. First, they identified the major firms conducting research on agricultural inputs and then tracked each firm's spending on agricultural R&D over time. The sum of R&D spending among these firms, plus an allowance for R&D spending by small and mid-sized firms, provided an estimate of total private R&D for agriculture.

Firms were classified into seven input sectors: three for crop inputs (seeds/biotechnology, pesticides, and fertilizers), three for animal inputs (animal breeding, health, and nutrition for food animals and aquaculture), and the farm machinery sector. Industry associations and private consulting firms[2] specializing on agricultural input markets were contacted to identify leading firms in each input sector. For publically-traded firms, annual financial filings usually contain data on sales and R&D (unless R&D is an insignificant part of costs, in which case it is unlikely to be reported). Firms that manufacture products for both agricultural and non-agricultural sectors usually report sales by business segment but may not report agricultural R&D separately from other R&D. For firms that did not report agriculturally-related R&D separately from their total R&D spending, agricultural R&D was estimated either by contacting the firms directly for this information, prorating R&D across the firm's business segments in proportion to sales, or using an industry-average research intensity (R&D as a fixed percentage of sales). Similar approaches were used to obtain estimates of R&D spending by privately-held firms that did not published financial reports (although many such firms report sales and R&D information on their websites, at least for current years).

While Fuglie et al. (2011) were able to identify several hundred companies world-wide doing some formal agricultural R&D, they found that the largest 5–10 firms in each sector accounted for 80% or more of total R&D in that sector. Thus, trends in private agricultural R&D spending are driven by the investment decisions of a few large firms. Since most of the large firms publish audited financial reports annually, the aggregate R&D estimates should be reasonably accurate. Moreover, since R&D spending is often given a different tax treatment from other types of costs, firms are required to report R&D using standardized accounting criteria. Situations in which this approach does less well is when R&D in a sector is dominated by many small firms or when the dominant firms in a sector are privately-held and don’t disclose financial information. In the 1990s, many biotechnology start-up companies invested in agricultural R&D, and it is difficult to get an accurate estimate of R&D spending by these firms (though they appear to make up a small part of the industry total). A similar situation may exist today regarding R&D for precision agriculture by IT firms, which is discussed later in this paper. The animal breeding sector is one in which there is a high degree of concentration (a few firms dominate poultry and pig breeding worldwide), but which are mostly privately held and don’t make public their financial information.

The present study uses the same approach as Fuglie et al. (2011) and extends the estimates from 1990 to 2014. In the course of the current investigation several new firms were identified that have significant agricultural R&D programs. The present study also draws upon new evidence on private agricultural R&D spending in India (Pray and Nagarajan, 2014)[3] and China (Bryant, 2007; Hu et al., 2011; Zhi, 2013; CCM, 2014; Harkell, 2015).[4]

In total, the present study tracked the agricultural R&D spending of 324 companies world-wide (Table 1). This includes 182 companies that were operating in 2014 and 142 legacy firms

[2] Industry associations include Croplife International, the International Federation for Animal Health, the International Seed Federation, the Association of Equipment Manufactures, the International Fertilizer Association, the International Feed Industry Federation, and related regional and national associations. Consulting firms that specialize in global agricultural input markets include Agribusiness Intelligence (a division of Informa plc), Cropnosis for crop sectors, Vetnosis for the animal health sectors, and VDMA for farm machinery. Agricultural input firms may also publish special reports of their industries or include information of their markets and major competitors in their annual reports. In particular, Alltech publishes an annual survey of the global animal feed industry and Potashcorp publishes annual overviews of the global fertilizer industry.

[3] The author would like to extend a special thanks to Carl Pray and Latha Nagarajan for making available their firm-level data on agricultural R&D spending by private firms in India.

[4] Agricultural input industries in China have been highly fragmented, composed of many small manufacturers with little or no internal R&D (Pray and Fuglie, 2001; Bryant, 2007; Zhi, 2013). Companies with significant intramural R&D spending only appeared in the late 1990s. The estimates of private R&D by Chinese companies in the paper incorporate newly available estimates of R&D by leading Chinese seed companies from a survey conducted by the Ministry of Agriculture (reported in CCM, 2014) and by animal health companies from a survey by the China Veterinary Drugs Association (reported in Harkell, 2015).

Table 1A
Number of companies in the R&D database.

Sector	Current in 2014	Legacy companies	Total
Crop R&D	105	121	226
Animal R&D	45	17	62
Farm machinery R&D	36	4	40
Total[a]	182	142	324

[a] Sum is less than total because companies may conduct R&D in multiple sectors (i.e., four companies conducted R&D in both the crop and animal sectors).

Table 1B
Companies by region based on country of incorporation.

Region	Crops	Animals	Farm machinery
USA-Canada	92	19	13
Europe-Middle East	70	32	13
Asia-Pacific	55	10	14
Latin America	9	1	0
Total World	226	62	40

None of the companies in the database are based in Africa.

(firms that operated at some time during 1990–2013 but had been acquired by or merged with another firm or had otherwise exited the agricultural input sectors). About 70% of these firms (226) conducted research on crops (seeds, agricultural chemicals, or crop nutrition), about 20% (62) focused on animals or fish (breeding, health, or nutrition), and the rest (40) were manufacturers of farm machinery (Table 1A). Regionally, about three-quarters of the firms were based in either USA-Canada or Europe-Middle East, 24% in the Asia-Pacific countries (Japan and India, especially), and about 3% in Latin America. No Africa-based firms with significant agricultural R&D were identified in the survey (Table 1B).[5] The company representation for Latin American appears low, but, as will be described later in the paper, private agricultural R&D is likely high because of significant investment by foreign multinational companies in this region.

Table 2 lists 110 companies in the database that were estimated to have spent at least $10 million on agriculturally-related R&D in 2014. Five companies (four in the crop sector and one farm machinery company) had agricultural R&D budgets greater than $1000 million. Most companies focused their agricultural R&D on either crops, animals or farm machinery, although a few had significant R&D in both crops and animals. R&D by farm machinery companies is also mostly focused on crop operations, but for expository purposes it is left as a separate category.

The list of companies in Table 2 contain several from developing countries. One of these largest in ChemChina,[6] a Chinese manufacturer of agricultural and other chemical products. But the animal R&D assigned to ChemChina in Table 2 is actually by its subsidiary Adisseo, a France-based animal nutrition company that ChemChina purchased in 2006. ChemChina also purchased (in 2011) the Israel-based agricultural chemical company Adama (formerly known as Makhteshim Agan Industries), which conducts R&D on crop protection chemicals.[7] This illustrates the dilemma about how to assign R&D by multinational companies to specific countries, or even global regions. Though Adisseo and Adama are now under Chinese corporate ownership, they did not shift their R&D programs to China following their acquisition by ChemChina. On the other hand, these companies were likely to already have been making R&D investments around the world to service and promote their global product sales. However, we might expect more of their R&D activity to gradually shift over time toward China as these activities are integrated with ChemChina's overall R&D activities and market foci.

While changes in corporate ownership do not affect the global estimate of private R&D spending, it does have implications for how we might allocate this R&D to specific countries or regions. Since firms rarely report R&D spending by geographic market, some rule must be applied to allocate their R&D by location. Fuglie et al. (2011) assigned all R&D of a company to the country where the parent company had its corporate headquarters, although they noted that many multinationals operated global networks of R&D laboratories and field stations and conduct a substantial portion of the R&D in foreign countries.

In this paper, two approaches are used to allocate private R&D to countries or regions. First, following Fuglie et al. (2011), private R&D is assumed to take place in the country where the corporate headquarters is located. The second approach is to assume that a firm's R&D follows the firm's product markets. Companies with significant foreign sales will usually break down product sales by global region in their annual reports. For companies with at least $100 million in agricultural R&D in 2014, their R&D spending is then apportioned to global regions according to that region's share of company sales.

Besides location, it is also of interest to examine how private R&D might be allocated across different commodities. Again, firms do not report R&D spending by commodity. However, industry-level estimates of the size of global agricultural input markets are available, and total private crop and animal R&D can be allocated in proportion to commodity shares in these markets. Commercial seed and chemical sales by commodity are from PhillipsMcDougall (part of Informa plc). Estimates of animal health inputs by species are from Vetnosis, animal nutrition inputs by species are from Alltech, and animal genetics inputs by species are from unpublished survey information collected from animal genetics companies by Fuglie et al. (2011). Note that the animal sector includes cattle, pigs, poultry, and aquaculture.

Although the focus of this paper is on agricultural R&D, for comparison purposes R&D spending by the food industry is also updated. The OECD reports R&D spending by food manufacturing companies for OECD-member countries and several emerging economies. Besides high-income countries, data are available for Argentina, Chile, Mexico, China, Turkey, South Africa and Russia. For Brazil, food industry R&D is from IBGE. For India, estimates are reported in Pray and Nagarajan (2014). For some countries, these sources may only report food R&D spending for intermittent years, and in these cases missing data are interpolated using the growth rate of the country's manufacturing sector. For other countries, no food R&D data are available, and in these cases food R&D is assumed to be zero. For this reason, figures for total global food industry R&D is likely under-estimated.

[5] Surveys by ASTI and Assess to Seeds (2016) have identified a number of firms doing agricultural research in Africa. However, agricultural research spending by indigenous African companies appears to be quite small, with most spending far less than $1 million annually on R&D. The one exception may be Pannar, a South African seed company that operates in several African countries. However, no financial data is publically available for Pannar. Pannar was acquired by Dupont in 2013.

[6] ChemChina is state-owned enterprise. It is also known as the China National Chemical Corporation.

[7] ChemChina is also currently negotiating the purchase of Syngenta, a Swiss-based company with over $1 billion in crop R&D in 2014. Together with its acquisitions of Adisseo and Adama, this would make ChemChina one of the largest agricultural technology companies in the world.

Table 2
Companies spending at least $10 million on agricultural R&D in 2014.

Ag R&D Spending USD/year	Farm Machinery	Animals Health, genetics, nutrition	Crops Seed, chemicals, irrigation, agronomy	
> $1 billion	Deere (USA)		Bayer (Germany)** Dupont (USA)** Monsanto (USA)** Syngenta (Switz)**	
$500–$999 m	CNH (Neth)		BASF (Germany)** Dow (USA)**	
$100–$499 m	AGCO (USA) CLAAS (Germany) Kubota (Japan)	Alltech (USA)ˋ Bayer (Germany) BIV (Germany) Lilly [Elanco] (USA) Merck (USA) Sanofi [Merial] (France) Zoetis (USA)	FMC (USA)* KWS (Germany) Limagrain (France) Rijk Zwaan (Neth) Sumitomo (Japan)*	
$50–$99 m	First Tractor (China) Iseki (Japan) Trimble (USA) Yanmar (Japan)	Adisseo [ChemChina] (China)ˋ Cargill (USA)ˋ Ceva (France) Cobb-Vantress [Tysons] (USA)† DSM (Germany)ˋ EW Group (Germany) Groupe Grimaud (France)† Virbac (France)	Florimond Esprez (France) Stine Seeds (USA) Sime Darby (Malaysia)++	
$10–$49 m	ARGO (Italy) Bucher (Kuhn) (Switz) Escorts (India) Exel (France) Lemken (Germany) M & M (India) Raven Industries (USA) SAME (Italy) SinoMach (China) TAFE (India) Topcon (Japan)	BASF (Germany)ˋ Danavl (Denmark)† Danisco [Dupont] (USA)ˋ Degussa [Evonik] (Germany)ˋ Genus (UK)† Hendrixs Genetics (Neth)† Land O'Lakes (USA)ˋ Marine Harvest (Norway)† Norbrook (UK) Novozymes (Den)ˋ Nutreco (Neth)ˋ Pharmaq (Norway) Ringpu Biological (China) Smithfield [Shanghu Int'l] (China)† Topigs Norsvin (Neth)† Vetoquinol (France)	Adama [ChemChina] (China)* Advanta (India) Albaugh (USA)* Arystra (Japan)* Barenburg (Neth) Bejo (Neth) Ceres (USA) Chemtura (USA)* DFL (Denmark)* East West Seed (Thailand) Enza (Neth) Euralis (France) Evogen (Israel) FGI [Land O'Lakes] (USA) Gowan (USA)* Hokka (Japan)* In Vivo (France) Isagro (Italy)* ISK (Japan)* Kaneko (Japan) Kumiai (Japan)* Lantmannen (Sweden) Maisadour (France)	Marrone (USA)# Mitsui (Japan)* Mosaic (USA)* Nestles (Switz)++ Netafim (Israel)+ Nihon Nohyaku (Japan)* Nippon Soda (Japan)* Nissan (Japan)* *Novozymes (Denmark)# Nufarm (Australia)* RAGT (France) Rotam (China)* Saaten Union (Germany) Sakata (Japan) Semillas Fito (Spain) SinoChem (China)* Takii (Japan) Vibha (India) Viterra [Agrium] (Canada) Wilmar Int'l (Sing)* Yara Int'l (Norway)* Yuan Longping (China)

Firms within each segment are listed alphabetically, with [parent company] and (country of incorporation) in parentheses.
Animal companies conduct primarily animal health R&D except for companies indicated by the following: †Animal & fish genetics; ˋNutritional feed additives.
Crop companies conduct primarily seed-biotech R&D except for companies indicated by the following: *Chemical pesticide and/or fertilizer only; **Combined R&D on crop seed, biotechnology, and agricultural chemicals; ++plantations and/or food manufacturing; +precision irrigation; #biologicals.

3. Findings

3.1. R&D investment trends by global agribusiness

The study finds that between 1990 and 2014, private agricultural R&D spending world-wide more than tripled, from $5.1 billion to more than $15.6 billion per year in nominal US dollars (Table 3), or from $6.4 billion to $12.9 billion in constant 2005 PPP$[8] (Table 4). Also in 2005 PPP$, total private R&D for both food and agriculture rose from $12.8 billion to $30.8 billion during 1990–2012 (food R&D estimates are only available through 2012). By way of comparison, total global public agricultural R&D expenditures were around $32–34 billion in 2008–2009 in 2005 PPP$ (Bientema et al., 2012; Pardey et al., 2015a). According to the estimates in Table 3, the growth rate in nominal private agricultural R&D spending accelerated after 2003, from around 3% per year during 1990–2003 to over 7% per year between 2003 and 2014. Trends in private agricultural R&D spending mirrored trends in companies' revenue from agricultural input sales. In turn, there is a strong correlation between trends in private agricultural input sales and farm commodity prices: 2002 was the year in which the FAO's world food price index reached its nadir; afterwards it began to rise, more than doubling by 2008.

Higher commodity prices increased farmers' ability and willingness to spend more for purchased inputs, including the latest technologies, to raise agricultural yields. With a higher crop price,

[8] Companies usually report their financial data in their national currencies, using current market exchange rates to convert foreign revenues and expenditures. To obtain global expenditures in nominal US$, this study used current market exchange rates from World Development Indicators. To convert spending into constant PPP$, nominal US$ expenditures were first adjusted for inflation using the U.S. implicit GDP price index (2005 = 1.00), and then converted to constant 2005 PPP$ using the national ratios of market US$ and PPP$ exchange rates for 2005 from the World Development Indicators.

Table 3
Private sector R&D expenditures for food and agriculture world-wide, 1990–2014.

Year	Crop protection chemicals	Crop seed & biotech	Crop fertilizer	Animal health (food sp.)[a]	Animal genetics	Animal nutrition	Total crop R&D	Total animal R&D	Farm machinery R&D	Total agricultural R&D	Food industry R&D	Total food & ag R&D[b]
	Millions of nominal U.S. dollars											
1990	2160	1175	63	532	171	213	3398	915	825	5138	5315	10,241
1991	2188	1244	59	577	177	218	3491	971	869	5331	5315	10,428
1992	2234	1281	62	628	183	224	3577	1034	875	5487	5786	11,049
1993	2347	1374	59	638	189	231	3781	1057	889	5727	6098	11,594
1994	2442	1505	61	650	196	238	4008	1083	915	6006	6340	12,108
1995	2532	1578	80	729	203	245	4189	1177	957	6323	7244	13,322
1996	2664	1655	84	783	210	254	4403	1246	1082	6731	6871	13,349
1997	2768	1838	64	784	217	268	4671	1269	1093	7032	6835	13,599
1998	2738	2074	56	768	225	274	4867	1267	1140	7275	6789	13,789
1999	2451	2064	49	741	232	285	4564	1258	1237	7060	6880	13,655
2000	2259	2318	56	721	240	295	4633	1256	1268	7157	6933	13,795
2001	2143	2218	53	657	249	307	4413	1212	1282	6908	7104	13,705
2002	2089	2027	56	659	258	322	4172	1238	1260	6671	7490	13,839
2003	2466	2129	74	747	267	339	4669	1353	1275	7297	8900	15,858
2004	2637	2261	97	814	276	355	4996	1445	1371	7811	9842	17,298
2005	2703	2364	119	870	285	364	5186	1520	1492	8198	10,635	18,468
2006	2649	2580	99	930	295	374	5328	1600	1652	8580	11,010	19,215
2007	2784	2865	104	1064	306	381	5753	1751	1919	9423	11,278	20,319
2008	3062	3395	96	1163	316	406	6553	1885	2196	10,634	13,492	23,720
2009	3063	3626	100	1131	327	417	6789	1875	2479	11,143	14,342	25,068
2010	3252	4032	100	1179	339	469	384	1987	2634	12,004	14,952	26,488
2011	3496	4523	103	1288	351	506	8121	2144	3072	13,338	17,054	29,886
2012	3599	4740	102	1338	363	555	8441	2256	3482	14,179	18,026	31,650
2013	3859	5039	103	1403	376	582	9000	2360	3702	15,063		
2014	4007	5357	103	1433	389	627	9467	2449	3691	15,606		

[a] Animal R&D includes R&D on food species only (excluding) R&D on companion and equine species).
[b] Sum of agricultural R&D and food industry R&D may exceed total because some agricultural R&D is conducted by food companies (e.g., R&D on animal feed).

Table 4
Private R&D expenditures for food and agriculture world-wide in constant PPP dollars.

Year	All Crop R&D	All Animal R&D (food sp.)[a]	Farm Machinery R&D	Agricultural R&D	Food Industry R&D	Total Food & Ag R&D[b]
	Millions of constant 2005 PPP dollars					
1990	4139	1188	1065	6392	6419	12,811
1991	4115	1217	1080	6412	6163	12,575
1992	4129	1265	1058	6452	6610	13,062
1993	4263	1261	1041	6565	6775	13,341
1994	4431	1256	1053	6740	6880	13,620
1995	4556	1344	1090	6990	7642	14,632
1996	4759	1401	1224	7384	7217	14,601
1997	4981	1407	1227	7615	7167	14,782
1998	5137	1404	1264	7805	7083	14,888
1999	4746	1379	1312	7437	7001	14,438
2000	4631	1348	1325	7304	6982	14,287
2001	4299	1275	1321	6896	7057	13,953
2002	4052	1288	1282	6621	7342	13,963
2003	4443	1384	1276	7104	8345	15,449
2004	4629	1444	1337	7410	9149	16,559
2005	4680	1484	1416	7580	9750	17,330
2006	4721	1543	1525	7789	9864	17,653
2007	5007	1659	1742	8409	10,516	18,925
2008	5592	1778	1990	9360	12,909	22,270
2009	5797	1775	2247	9819	14,120	23,940
2010	6274	1880	2363	10,517	14,845	25,361
2011	6816	1999	2705	11,520	17,098	28,618
2012	6964	2087	3017	12,068	18,690	30,758
2013	7277	2172	3152	12,601		
2014	7581	2229	3091	12,900		

[a] Animal R&D includes R&D on food species only (excluding R&D on companion and equine species).
[b] Sum of agricultural R&D and food industry R&D may exceed total because some agricultural R&D is conducted by food industry companies (e.g., R&D on animal feeds).

the value of any yield gain increases. A higher price of corn, for example, would make latest hybrid varieties more profitable to adopt, even though these might cost 20–30% more than older hybrids. But whether higher the revenue earned by input companies would translate into higher R&D investment depends on whether companies view higher commodity prices as long-term or cyclical. It may take several years to realize returns to R&D, and it may not be in a company's interest to increase investment in R&D only to find demand for new technologies waning by the time that R&D delivers improved products for sale. The strong private sector R&D response, doubling its agricultural R&D spending between 2003 and 2013, suggests that higher commodity prices were expected to persist for some time. In fact, company websites and corporate reports make frequent references to the need to raise long-term agricultural productivity, due to rising populations and limited land and water resources, and such concerns are typically cited as justification for a firm's investment in agricultural R&D.

The bulk of private agricultural R&D is conducted by a relatively small number of companies (Table 5). The 23 "top tier" companies listed in Table 2 (those estimated to have spent at least $100 on agricultural R&D in 2014) together accounted for over 70% of total global agricultural R&D by the private sector. The 110 companies identified in the survey that spent at least $10 million in agricultural R&D in 2014 accounted for 88% of the global total. Admittedly, the estimate for R&D spending by companies with less than $10 million in agricultural R&D is the least precise part of the estimate, since R&D spending by many small companies is not directly observed but imputed. Given the small amount of R&D estimated for companies, even a fairly large error in this estimate would not have a substantial effect on the global total.

Table 6 provides an estimate of private agricultural R&D by commodity. This estimate is derived by allocating total R&D for crops and animals in proportion to the share of agricultural inputs

Table 5
Private agricultural R&D spending by company size in 2014.

Annual R&D spending	Crop R&D		Animal R&D		Farm machinery R&D		All ag input R&D		
	Firms (no.)	R&D (m$)	Firms (no.)	R&D (m$)	Firms (no.)	R&D (m$)	Firms (no.)	R&D (m$)	R&D (%)
> $1000 m	4	5178	0	0	1	1162	5	6340	39%
$500–999 m	2	1581	0	0	1	519	3	2100	13%
$100–499 m	5	948	7	1,522	3	900	15	3370	21%
$50–99 m	3	228	8	607	4	257	15	1092	7%
$10–49 m	44	1011	15	374	12	266	70	1684	10%
< 10 m	NA	484	NA	481	NA	587	NA	1551	10%
All companies > $100 m	11	7707	7	1522	5	2581	23	11,810	73%
All companies > $10 m	58	8979	30	2504	21	3104	109	14,586	90%
Total business sector		9462		2984		3691		16,347	100%

Note: Total animal and total input R&D shown above is higher than the totals reported in Table 3 because Table 3 excludes animal health spending on companion and equine species.
NA=not available. (m $)=millions of US$.

Table 6
Private crop and animal R&D by commodity in 2014.

Commodity	R&D (million US$)	R&D Share (%)	R&D relative to value of commodity (%)
Corn	2645	28.1	1.83
Soybeans	1765	18.8	2.33
Vegetables & fruit	1774	18.9	0.31
Wheat and small grains	1006	10.7	0.68
Rice	630	6.7	0.30
Cotton	461	4.9	0.91
Other oilseeds	518	5.5	1.59
Sugar crops	261	2.8	0.36
All other crops	341	3.6	0.10
Total Crop R&D	9400	100.0	0.57
Ruminants	730	33.3	0.15
Poultry	727	33.2	0.32
Pig	623	28.5	0.36
Aquaculture	109	5.0	0.07
Total Animal R&D	2189	100.0	0.21

R&D by commodity is found be apportioning total R&D by the commodity's share of total purchased inputs.
Small grains include barley, oats and rye.
Other oilseeds include canola, rape, and sunflower.
Sugar crops include sugar beets and sugarcane.
Sources: R&D estimates from this study; value of production from FAO.

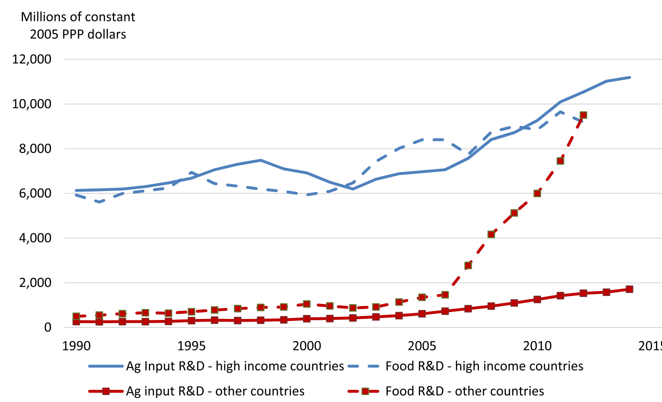

Fig. 1. Trends in private agricultural and food R&D spending in high-income vs. other countries. High-income countries include USA, Canada, Japan, South Korea, Taiwan, Australia, New Zealand, and Europe except Turkey, Russia and Belarus.

used by that commodity. The largest private agricultural R&D efforts were for corn ($2647 million in R&D), soybeans ($1766 million in R&D), and vegetables and fruit ($1775 million in R&D). But perhaps a better ranking is to compare R&D spending relative to the gross value of commodity production. Corn, soybeans and other oilseeds rank far above all other commodities in this measure, with private R&D effort amounting to 1.8%, 2.3%, and 1.6% of the value of these crops, respectively. For other commodities, including animals and fish, private R&D was less than 1% of the value of production. Important world agricultural commodities not receiving much attention from private R&D include root and tuber crops (potato, cassava, and sweet potato), bananas and plantains, many species of vegetables and fruit crops, small-holder tree crops (coffee and cacao), ruminants, and aquaculture. Regarding aquaculture, most of the private R&D identified in this study was focused on salmonid species (salmon and trout), and private R&D relative to the value of these species is probably around 2%. Private R&D spending on non-salmonid species appears to be quite low.

The great majority of private agricultural R&D spending is by companies based in developed countries, although their aggregate share has fallen over time. Fig. 1 breaks out trends in R&D spending by agricultural input firms and food manufacturing firms based in high-income countries from firms from other countries during 1990–2014. By 2014, about $11.2 billion out of the total $12.9 billion of total private agricultural R&D, or 87%, was by firms based in high-income countries. But this share was down from 94% of total private agricultural research in 1990. However, in food R&D, a rapid rise in reported R&D spending by Chinese firms apparently closed the gap with high-income countries by 2012. Pardey et al. (2015a) report a similar trend in their estimate of private food and agricultural R&D spending in developed and developing countries, but do not break out food R&D from agricultural R&D.[9]

Although 88% of global private agricultural R&D spending was by companies based in high income countries, a significant part of this R&D is likely targeted toward developing-country farmers. If we assume that companies allocate their R&D around the world in proportion to where they sell their products, the share of private agricultural R&D for developing countries rises to 28% for the top tier companies (Table 7). Moreover, this share was rising over time. By 2014, nearly a fifth of the agricultural input sales of these

[9] Pardey et al. (2015a) estimated global food and agricultural R&D spending by the private sector at $26.8 billion in 2009, which is somewhat higher than this study's estimate of $23.9 billion for that year (both estimates in 2005 PPP$). A possible reason for Pardey et al.'s higher estimate is that they imputed food and agriculture R&D spending for a much broader set of countries based on an econometric model. Their model assumed that private food and agricultural R&D in a country is correlated with per capita GDP, public agricultural R&D, and total national R&D. They estimated the model using data from middle-income and high-income countries and then used it to derive estimates of R&D spending in low income countries (Pardey et al., 2015b). It is unclear how well this approach predicts R&D spending for countries at substantial different development levels from the observed data, or whether it primarily reflects food R&D or agricultural R&D.

Table 7
Estimates of agricultural R&D of top tier companies by global region in 2014.

	North America	Europe-Middle East	Asia-Pacific	Latin America	Emerging Markets	World
Assign all company R&D according to country of incorporation						
Private R&D by top tier companies (million US$)	6139	5092	524	0	0	11,755
% of total	52	43	4	0	0	100
Assign company R&D in proportion to regional sales of agricultural inputs						
Private R&D by top tier companies (million US$)	4606	3397	1507	2245	3275	11,754
% of total	39	29	13	19	28	100

Top tier companies include the 23 companies listed in Table 2 that had at least $100 million in agricultural R&D in 2014.
Europe-Middle East includes Africa.
Emerging Markets: China, India, Turkey, South Africa, Brazil, Argentina, Mexico and other developing countries.

companies was in Latin America alone. While the Latin American-based companies tracked in our survey spent in total only $31 million on agricultural R&D in 2014, R&D spending by multinationals for Latin America could have been as high as $2245 million when allocated proportionally to regional sales of agricultural inputs.

A rare published breakdown of agricultural R&D by region by the Swiss company Syngenta offers an opportunity to assess this approach to allocating R&D by location. In its 2002 Annual Report, Syngenta reported that 54% of its R&D employees (who numbered 4149 at that time) were located in the Europe-Middle East-Africa region, 27% in North America, 8% in Latin America, and 11% in Asia-Pacific countries. In that year, the corresponding geographic segment shares of its agricultural seed and chemical sales were 38%, 36%, 11%, and 15%, respectively. Clearly, assigning all of Syngenta's R&D to Switzerland, or even to Europe, understates its relevance for world agriculture. Allocating its R&D in proportion sales would provide a better approximation, although it would understate its R&D spending in its home region – Europe.

3.2. Private agricultural R&D in developing countries: the role of technology policy

The evidence above suggests that the private sector is increasingly important for agricultural innovation and productivity growth not only in developed but also developing countries. However, while the data are incomplete, it appears that for many low and middle income countries, there is little evidence of much private investment in agricultural R&D. A recent review article by Pray and Fuglie (2015) found that technology policy can have a significant influence on private agricultural R&D spending in developing countries, including by foreign companies. In particular, they found that policies toward biotechnology, intellectual property rights, and allowing participation of multinational corporations in national agricultural input markets affected the willingness of private firms to investment in agricultural R&D. The paragraphs below draw from their study to contrast different policy approaches pursued by Brazil, India and China to incentivizing private agricultural innovation in their countries, and what lessons this may hold for other developing countries.

Brazil has taken a relatively liberal policy toward multinational participation in their domestic agricultural input markets, allowing foreign companies to operate wholly-owned subsidiaries in the country and acquire domestic companies. Brazil also established intellectual property rights for new crop varieties and regulatory protocols for approving the use of GM crop varieties. Brazil is one of the fastest growing markets for agricultural inputs, and several multinational companies have established agricultural research stations in the country. Agricultural R&D spending by private companies increased from $50 million in 1996 to $377 million in 2012, almost all of which way by foreign companies (Pray and Fuglie, 2015). This amounts to about 20% of total public and private agricultural R&D spending in Brazil in 2012 (public agriculture R&D in Brazil $1560 million that year, according to Pray and Fuglie, 2015).

India's agricultural input markets were largely closed to the private sector until the 1990s. Reforms in that decade removed import restrictions, established plant breeders' rights, and allowed domestic and foreign companies to participate in agricultural input markets. Meanwhile, the government reduced its support for or privatized state-owned enterprises that had previously dominated input markets (Pray and Fuglie, 2015). India also permitted the use of GM varieties in cotton. According to a survey of agribusiness companies (Pray and Nagarajan, 2014), private agricultural R&D in India increased from $44 million in 1995 to $271 million in 2009, with 38% of this spending by foreign multinationals and 62% by Indian firms. Not only were Indian seed, pesticide, and farm machinery companies able to compete with foreign companies in the Indian market, some had expanded into foreign markets as well. With public agricultural R&D at $895 million in 2009 (ASTI), the private sector accounted for nearly one-fourth of total public and private agricultural R&D spending in India.

Despite being the world's largest agricultural producer, China has restricted foreign company participation in seed and other agricultural input markets to minority shares in joint ventures with Chinese firms (Pray and Fuglie, 2015). In addition, enforcement of intellectual property laws is seen as relatively weak, approval of GM crop varieties has been limited to cotton, and state-owned companies continue to play a major role in supplying agricultural inputs to Chinese farmers. While many foreign multinationals have engaged in agricultural research in China (often in collaboration with a Chinese institution or company), their agricultural R&D investment in China has been relatively modest. A survey of 1305 Chinese agribusiness firms, including state-owned enterprises and firms with foreign joint ventures, estimated that their combined spending on agricultural R&D (not including funds from the government) was $244 million in 2006 (Hu et al., 2011). With a relatively low level of private agricultural R&D, agricultural research in China continues to be dominated by public institutions. Public agricultural R&D spending in 2006 was $1934 million (Pray and Fuglie, 2015).

Despite low levels of agricultural R&D spending by foreign or domestic firms in China, Chinese companies have used direct acquisitions of foreign companies to gain access to their capacities and technology. Previously mentioned were the acquisitions by the state-owned enterprise ChemChina of the France-based specialty feed company Adisseo (for $500 million in 2005) and the Israel-based agricultural chemical company Adama (for $2.4 billion in 2011). In 2011, the privately-owned Chinese company Shuanghui International acquired the U.S.-based meat processing company Smithfield Foods for $4.72 billion, including its subsidiary Smithfield Premium Genetics, one of the world's largest privately-held pig breeding operations. In the same year the state-owned Chinese machinery manufacturer Sinomach acquired McCormick France Corporation, a French farm machinery parts manufacturer. But by far the most significant potential acquisition is of Syngenta by ChemChina. In February 2016, ChemChina's $43 billion offer was accepted by Syngenta and is currently undergoing regulatory review. Our survey indicates that the agricultural R&D spending in 2014 by all of these foreign acquisitions was $1.49 billion ($1.38 billion by Syngenta alone).

The experiences of Brazil, India and China outline three distinct approaches for developing countries to attract and build capacity in private agricultural R&D. By one measure – total private R&D investment in the country – Brazil's open-door policy has been the most successful. It mobilized the R&D capacity of multinational agribusiness to make new technologies available to Brazilian farmers, and at very little direct cost to the Brazilian economy. India's economic reforms gradually reduced the role of state-owned enterprises in supplying agricultural inputs to farmers and encouraged not only domestic but also foreign businesses to fill that gap. While total agricultural R&D investment in India has been significantly below that of Brazil (around $271 million per year in India versus $377 million per year in Brazil in the late 2000s), more than half of that investment was by Indian firms. Some of these have emerged as multinationals themselves, successfully competing with their own brands in international chemical, seed, and farm machinery markets. China, despite a much larger agricultural sector, appears to have mobilized even less private agricultural R&D spending than India, nearly all of which is by domestic firms. While China has been less successful in attracting foreign companies to invest in agricultural R&D in China, it has been able to access foreign technology through direct acquisitions of foreign firms. This strategy may speed up transfer of technology assets to China and preserve a larger degree of sovereign control, but is financially costly to the Chinese economy.

3.3. Venture capital: attracting new entrants and new technologies to agriculture

The approach taken in this paper to assess the level and direction of agricultural innovation by the private sector has been to track R&D spending of the major companies in agricultural input sectors. A limitation of this method is that it may miss new entrants, especially by small and medium-size enterprises (SME). New SME entrants, often funded through venture capital or angel investors, can be of particular importance for early stage development of a new types of technologies. SME's provide a useful platform for experimentation and for attracting new expertise and talent to the field. Similar to the role SME's played in developing agricultural biotechnology in the 1980s, they may now be playing a major role in developing information technology (IT) applications for agriculture, or what is commonly referred to as precision agriculture.[10]

A useful source of information on SME innovation activity is venture capital (VC) funding. Corporate and institutional investors make extensive use of VC to explore high-risk but potentially transformative technologies. VC has arisen has a financing tool for investors in situations where there are large differences between what investors and entrepreneurs know about technological opportunities, but where entrepreneurs may have few tangible assets that would enable them to seek traditional forms of capital financing (Gompers and Lerner, 1999). While only a portion of VC is for formal R&D (it also funds scaling up, integrating and field testing new innovations), trends in VC financing provide an indicator of where the business sector sees potential for new technologies to have transformative impacts in the economy.

In fact, there appears to have been a sharp rise in venture capital (VC) financing of SME's for food and agriculture innovations in the last few years, at least in the United States. Before 2013, U.S.-based VC funds for food and agriculture averaged $400–500 million per year, but then grew to $800 million in 2013, $2.4 billion in 2014, and $4.6 billion in 2015 (AgFunder, 2016). Table 7 breaks down how U.S.-based food and agriculture VC was allocated among several technology areas. Of the total VC of $6.9 billion during 2014–1015, $2.57 financed new agricultural innovations. More than $1 billion of this was used to fund 185 projects involving precision agriculture, including field sensors, satellite imagery, drones and robotics, and decision support tools to translate “big data” into real-time farm management advice. Many of the recipients of these funds were small start-up companies, including a cluster of Silicon Valley IT firms. Another $692 million funded projects for irrigation technology and management, and $482 million for projects involving biological and chemical treatments, GM traits and seed technologies to enhance crop nutrition and health. Although many if not most of the firms and projects funded by VC can be expected to fail, what could emerge from this investment is a new IT agricultural input sector with significant implications for resource use and productivity in agriculture.

4. Summary and implications

The importance of the private sector in developing new agricultural technologies for world agricultural has clearly increased over the past quarter century. Between 1990 and 2014, private spending on agricultural R&D rose from $5.14 billion to $15.61 billion per year, an increase of more than three-fold (or two-fold, in constant PPP$). This is faster than the growth in public agricultural R&D and in high-income countries, now constitutes the majority of total agricultural R&D (Bientema et al., 2012; Pardey et al., 2015a). The relevance of private R&D for developing country agricultural is also growing. Estimates in the paper suggest that as much as 28% of total private agricultural R&D (amounting to $4.3 billion in 2014) may be targeted toward farming conditions in developing countries. Moreover, private agricultural R&D spending was rising faster in developing countries than in developed countries.

The private sector appears to have demonstrated considerable agility in raising R&D investments at least partially in response to the commodity price increases of the past decade. When world prices for agricultural commodities began to rise after 2002, private investment in agricultural R&D accelerated, with the annual rate of increase rising from under 3% to over 7% (from 1% to 5% per year in inflation-adjusted dollars). Given the long lag times to realize economic returns from R&D investments, it would seem that private companies interpreted the rise in commodity prices as signaling a long-term tightening of global food supply-demand balances and not merely a short-term cyclical phenomenon. Their willingness to significantly increase spending on R&D suggests they expected heightened farm demand for productivity-enhancing technologies to persist well into the future. It will be interesting to see to what extent the recent drop in commodity prices will affect these expectations and the R&D investment decisions by these companies. Although data are incomplete, some large firms announced reductions in their R&D spending in 2015 and 2016.

The growing R&D capacity of the private sector carries implications for public policies toward agriculture and development. One key challenge is adjusting the public R&D portfolio so that is complements rather than crowds out private R&D. One way

[10] Precision agriculture can be defined as “the application of modern information technologies to provide, process and analyze multisource data of high spatial and temporal resolution for decision making and operations in the management of crop production” (National Research Council, 1997).

Table 8
Investments by U.S. venture capital funds for innovations in agriculture, food, and new uses for agricultural commodities during 2014 and 2015.Source: AgFunder (2015, 2016).

Sector	Innovation	Venture capital deals (number)	Venture capital investment (million $)
Agriculture	Precision agriculture	185	1077
Agriculture	Decision support tools & software	76	424
Agriculture	Drones & robotics	65	502
Agriculture	Sensor & mapping technologies	44	151
Agriculture	Irrigation & water management for crops	27	692
Agriculture	Crop health & nutrition (biologicals, chemicals, traits)	61	482
Agriculture	Indoor & greenhouse agriculture	38	252
Agriculture	Animal health & nutrition	17	66
Food systems	Food ecommerce marketing	159	2023
Food systems	Sustainable protein (meat substitutes)	13	360
Food systems	Food manufacturing technologies	28	135
Food systems	Food safety & traceability	29	144
Food systems	Waste technology	31	245
Food systems	Farm to consumer marketing	34	129
New uses - energy	Bioenergy	38	679
New uses - industry	Biomaterials & biochemicals	45	367
Other	Miscellaneous	85	213
Total agriculture		328	2569
Total food systems		294	3036
Total energy, industry and other uses for crop commodities		168	1259
Total, all sectors		790	6864

government science agencies and universities accomplish this is by focusing on basic or fundamental scientific research. But contemporary models of scientific and technological development processes suggest that relationships between basic and applied sciences are interactive and complex, and that there continues to be a role for targeted, applied R&D by public institutions, even in developed countries. There are also significant opportunities (and challenges) for mobilizing joint public-private investment in pre-commercial research and enhancing information flows between public and private R&D institutions (Fuglie and Toole, 2014).

An important target for public R&D is to address farmers' needs in areas where incentives for private R&D are low. From the data presented in this paper, it is apparent that the world-wide coverage of private agricultural R&D remains uneven. Private R&D in developing countries, while growing rapidly overall, has been heavily focused on middle-income countries. Low-income countries, especially those in Africa, have yet to attract substantial private R&D investment in their agriculture sectors. Even among middle countries, the willingness of the private sector to investment in agricultural R&D is conditioned by the policy environment, as the comparative experiences of Brazil, India and China attest to.

An important implication of this evidence is that the enabling environment for the private sector matters. Reasons why private companies have invested few R&D resources into some countries is that the institutions providing intellectual property right enforcement, regulatory frameworks, technology dissemination, farm credit and marketing services, are poorly developed (Pray and Umali-Deininger, 1998). A strong public agricultural research and university system can also be a draw for companies to locate research in a country, as it assures a pool of trained local talent and provides a stronger knowledge base to build upon (Pray and Fuglie, 2001).

Private R&D also appears to be uneven across commodities. While companies are pursuing at least some research on most of the world's cultivated crops and animal species, private R&D appears to be concentrated on a relatively small number of crops, especially corn and soybeans. Private R&D spending on wheat, rice, vegetables, cattle, pigs, and poultry is also considerable and growing, but still relatively low given the importance of these commodities to the global economy. And there are a range of other commodities where so far R&D investment by the private sector appears to be negligible – roots and tubers, most tree crops, small ruminants, and most species of farm-raised fish, for example. (Table 8).

Some of the public concerns that have been expressed about the rising role of the private sector in agricultural technology development include (i) loss of national control over food systems, especially if foreign multinational corporations become dominate suppliers of inputs to farmers, (ii) growth of monopoly power in input markets that could drive up input prices, (iii) technology determinism, where farmers choices may be limited to technologies favored by private developers, such as hybrid seed and GM crops, and (iv) a preference to serve the needs of large commercial farms at the expense of small holders. While exploration of these issues is beyond the scope of this paper, what is clear from the evidence is that the private sector has made major contributions to raising agricultural productivity in both developed and developing countries. Moreover, the technological portfolios, geographic and commodity coverages, and level of financial commitment of the private sector to agricultural R&D are expanding.

Disclaimer

The views expressed in this paper are the author's own and do not necessarily reflect those of the U.S. Department of Agriculture or the Economic Research Service.

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