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Passing the food and agricultural R&D buck? The United States and China

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ABSTRACT

The global geographical balance of food and agricultural R&D spending is shifting, characterized by a declining U.S. share and a rising middle-income-country share, propelled heavily by the rapid rise of spending in China. Based on our newly compiled data, we estimate that China now outspends the United States on both public and private food and agricultural research on a purchasing power parity basis. The public-private orientation of the research has also changed markedly, with the private sector now accounting for around two-thirds of the food and agricultural R&D spending total in both China and the United States. Our estimates indicate that China's private sector tilts heavily towards post-farm R&D activities, whereas the U.S. private sector is split more evenly between on-farm and post-farm spending. While the intensity of Chinese investment in food and agricultural R&D (relative to agricultural GDP) is beginning to grow, it still lags well behind the food and agricultural R&D investment intensities of the United States and other higher-income Asian countries (e.g., Japan and South Korea). The development regularities we reveal in the longer-run trends are indicative of future R&D investment patterns with potentially profound long-run implications for the size, shape and accessibility of the global stocks of scientific knowledge that underpin food and agricultural sectors worldwide.

1. Introduction

The global landscape for food and agricultural research and development (R&D) spending is shifting, with public spending by the middle-income countries now surpassing that of the high-income countries for the first time in modern history (Pardey et al., 2016a, 2016b). Over the past few decades, the U.S. share of global public-sector agricultural R&D spending dropped markedly from 20.2% in 1960 to 11.5% by 2011. Likewise, the U.S. share of private sector agricultural R&D spending worldwide has also shrunk, from 33.0 percent in 1980 to 24.5 percent in 2011. The declining U.S. share of a rising global agricultural R&D total is concordant with a rise in public and, to a generally lesser but certainly noteworthy extent, private agricultural R&D spending by the middle-income countries. India, Brazil and, especially, China account for much of the relative rise of the middle-income countries.

Investment in food and agricultural R&D is important for China to clothe and feed its growing population, now reaching almost 1.4 billion people, or 18.7 percent of the global total (U.S. Census, 2017). Moreover, the country's real per capita income topped $14,399 (2011 international, or purchasing power parity, PPP, dollars) in 2016, a remarkable 9.4-fold increase over the inflation-adjusted $1,526 per capita equivalent in 1990 (World Bank, 2017a). This unprecedented growth in per capita income also spurred a rapid rise in per capita calorie consumption—from 2,515 kcal per day in 1990 to 3,108 kcal per day in 2013—, and a shift in the composition of calories consumed (FAO, 2017). In 2013, 19.9 percent of Chinese calorie consumption came from livestock sources (meat, eggs, and milk) compared with 10.0 percent in 1990. Increasing food consumption and shifting dietary structures place significant strain on China's limited land and water resources. While food security concerns have long loomed large in national policy considerations (Timmer, 1976; Yang et al., 2008; Lam et al., 2013; PRC, 2016; Huang and Yang, 2017), how China fares regarding agricultural production and productivity also has global consequences given the country accounted for 21.8 percent of the 7,365.8 trillion calories consumed worldwide in 2013 (Pardey et al., 2014; FAO, 2017).

Although the United States has a smaller but sizeable population (presently 327 million people, U.S. Census, 2017) and much slower growth in per capita calorie consumption than China (0.2 percent per year versus 0.9 percent per year from 1990 to 2013), it remains a major source of global agricultural production and a major exporter of agricultural produce. In 2013, the United States was the top world producer (by gross value of production) of maize, sorghum, soybeans, cattle meat and cow milk, and the leading exporter (by value) of wheat, maize, sorghum, almonds, and pork meat (FAO, 2017). The U.S. position as a

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leading agricultural producer owes much to a century or more of solid, and at times rapid, growth in agricultural productivity (Andersen et al., 2018) fueled by significant investments in agricultural R&D (research and development) performed by public and private entities (Alston et al., 2010).

Transforming agricultural economies is a long-run endeavor, where history teaches us that R&D driven productivity growth is central to the process (Pardey and Alston, 2019). History also reveals that the effects of R&D can spill far and wide, well beyond the confines of the countries originally conducting the research. China and the United States are two countries with remarkable agricultural productivity growth records that together account for one third of the world's food and agricultural R&D spending R&D (Pardey et al., 2016a). Given their critical importance in shaping the world's agricultural production, trade and food security futures, in this paper we place their respective food and agricultural R&D spending records in an historical context to better understand the past, present and prospective future R&D spending developments in both countries.

To delve into United States-China agricultural R&D relativities, we draw on new and updated compilations of public and private food and agricultural R&D spending estimates for both countries. A substantive effort was made to ensure the U.S and Chinese R&D data are comparable both over time and between the two countries. This necessitated a significant revision of both the public and private sector spending series for China compared with almost all previous estimates published by some of the authors of this paper and many others (see the listing in Table S2 in the Supplementary Material).[1] Given the magnitude of our revisions to the Chinese data, we briefly describe some of the more salient features of the data revisions we introduce here in these spending estimates.

Our new data reveal a dramatic and, of late, remarkably rapid shift in spending relativities between the public and private sectors in both countries and between the countries themselves. We first describe and interpret these shifting relativities, and then assess if these changes are likely to persist in future decades. To do that we use especially long-run data for the United States, together with comparable R&D data for other higher-income Asian countries (specifically Japan and South Korea), to consider if the recent rapid changes in Chinese agricultural R&D spending have historical precedents in the patterns of high-income countries. We find some quantitative precedents in the United States, Japan and South Korea in the general character of the more recent Chinese developments, but with some notable and empirically significant differences. Our in-depth comparative assessment of the United States versus China R&D trends indicate some fundamental economic forces at play, which suggest that Chinese food and agricultural R&D spending is likely to continue growing as its agricultural sector grows and its food and agricultural R&D intensity deepens, although policy changes in either country would surely change the nature, magnitude and trajectory of their future spending relativities.

2. Measurement matters

Ensuring comparability between U.S. and Chinese food and agricultural R&D spending estimates involves attention to details regarding the nature and scope of innovative activity included in the respective country series, and standardizing the methods used to account for differences in the prices of R&D inputs over time and between the two countries.[2]

The U.S. public sector series used here has been maintained by the University of Minnesota's InSTePP (International Science and Technology Practice and Policy) center for many years. It includes food and agricultural R&D spending conducted by public institutions (mainly the United States Department of Agriculture, USDA, and the state agricultural experiment stations, SAESs).[3] Pardey et al. (2016c) provide details on the data sources (mainly USDA) and procedures used to compile these estimates, which closely follow OECD (2015) guidelines for reporting data on "research and experimental development." Here we report a revision of version 3.5 of the U.S. food and agricultural R&D series in the InSTePP Innovation Accounts, updated from 2013 to 2015 with data from USDA, CRIS (2015 and 2017).

The Chinese public-sector series used here is a completely new compilation. Beginning with one of the first such compilations by Fan and Pardey (1992), almost all subsequent published studies—including a series of publications and data products by IFPRI (Chen and Zhang, 2011; Beintema et al., 2012, Fig. 7; Chen at al., 2012; IFPRI, 2017a), USDA-ERS (Fuglie and Toole, 2014; Clancy et al., 2016; Fuglie, 2016), and CCAP (Huang et al., 2003, 2004; Hu et al., 2011) (see also Table S1 in the Supplementary Material)—report agricultural research spending indicators where the China-related data are tantamount to spending on "science and technology" (S&T) activities, not the narrower scope of R&D activities per se. In keeping with OECD (2015, pp. 70, 71 and 241) norms, the *China Statistical Yearbook on Science and Technology* (NBS and MOST, 1995, pp. 289 and 290)—which is jointly published by the National Bureau of Statistics (NBS) and the Ministry of Science and Technology (MOST)—, reports that their S&T series includes spending on R&D *and* related technical activities (such as technical testing, quality control and analysis, and technology transfer activities) that help move the results of R&D into actual production. The inclusion of these technical testing and transfer activities means that all the prior compilations of Chinese food and agricultural R&D estimates based on S

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[1] Exceptions are OECD (2016) and the China series incorporated in Pardey et al. (2015, 2016a, 2016b) and Pardey and Beddow (2017). The series presented here is constructed using the same conceptual and practical procedures used when developing the 2015, 2016 and 2017 compilations reported by Pardey et al. but is updated and incorporates some revisions of the historical estimates. Documentation for the Chinese estimates are provided in the Supplementary Material, and the time-series of these data used for this study are available at www.instepp.umn.edu/instepp-international-innovation-accounts.

[2] As Pardey et al. (2016c, p. 4) report, the InSTePP series includes food (and agriculturally related beverage) research in its compilation of "agricultural" R&D, which is the practical implication of the OECD's (2002, p. 145-146) guideline for what constitutes "agricultural production and technology" R&D. As Pardey et al. (2016c, p. 5) further elaborated "…[the] InSTePP series sought to include (on- and off-farm) research related to food, beverage and tobacco processing research in its food and agricultural R&D series. The methodology used to construct InSTePP's agBERD [private food and agricultural R&D gross expenditure] series overtly includes food, beverage and tobacco processing R&D. The agPERD [public food and agricultural R&D gross expenditure] series also strives to include food processing research in its scope of research, such that both the public and private series constitute a comparable and comprehensive compilation of food and agricultural R&D. The (pre-aggregated) nature of most of the available agPERD data means there is less measurement control over the scope of these series, but certainly some (and likely) many of the available public (food and) agricultural R&D totals include research related to food processing (and likely much of it carried out under the guise of research performed as part of the nutrition sciences). For example, this is so for the public food and agricultural R&D data available for the United States (see USDA-NIFA (2013) where food processing R&D is classified under the Knowledge Area Topic V, which is the category "Food and non-Food Products: Development, Processing, Quality, and Delivery")…" Here and throughout the remainder of the paper, for the aggregate series, we will use "agricultural" and "food and agricultural" R&D interchangeably, unless otherwise stated. When separate data series on "agricultural (net of food related)" and "food (net of agricultural)" R&D are discussed we distinguish them explicitly, as for example in section 4.4, where we identify on-farm agricultural input (net of food-related) R&D and post-farm food and beverage (net of agriculturally-related) R&D.

[3] The U.S. (and Chinese) food and agricultural R&D series presented here exclude spending on forestry research. Forestry research conducted by the SAESs and USDA totaled $469.8 million in 2015, around 10.6 percent of that year's food and agricultural R&D total of $4,414 million, inclusive of forestry research.

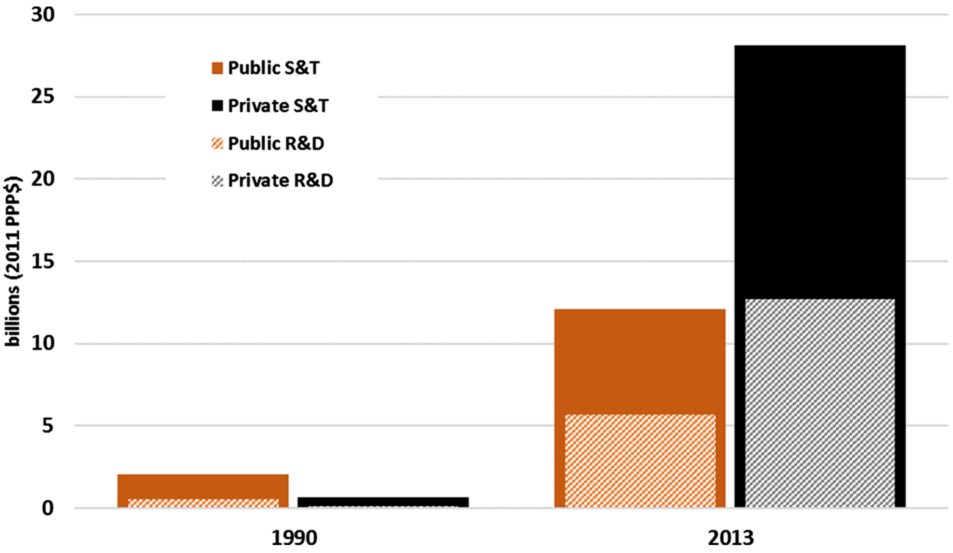

Fig. 1. Chinese S&T versus R&D Food and Agriculture Spending Relativities, 1990 and 2013. *Notes: "S&T" indicates science and technology and "R&D" indicates research and experimental development. Source*: Authors estimates based in sources tabulated in Table S2, Supplementary Material.

&T measures have overstated the amount spent on corresponding R&D activities in China.

The magnitude by which the prior Chinese agricultural R&D spending estimates are overstated is often substantial. For example, the ASTI series developed by IFPRI report that 27.2 billion yuan (current value) was spent on public "agricultural R&D" in 2011 (IFPRI, 2017a). However, this is 146 percent larger than a comparable "agricultural R&D" public-sector total (of 11.1 billion yuan) extracted from our new "food and agricultural R&D" estimates.[4] Drawing on the official Chinese data used to form our new estimates—and standardizing on comparable U.S. measures of food *and* agricultural R&D spending—Fig. 1 shows that public S&T spending in China in 1990 was 3.8-fold larger than the comparable R&D figure, and 4.6-fold bigger for private or industrial research. In 2013, the Chinese S&T to R&D differentials had shrunk but were still sizable: the public S&T estimate was 2.1-times larger and the industrial S&T figure was 2.2-times larger than the corresponding R&D estimates.

Official Chinese data sources have long reported S&T spending estimates but only began reporting estimates of R&D spending in 2001 (with both an S&T and R&D spending series being reported for the period 2001–2008 in the *China Statistical Yearbook on Science and Technology*). For the years when both series were reported, the pattern of change in S&T versus R&D spending was strongly correlated (with a correlation coefficient of 0.79), so we used the annual rate of change in S&T spending to backcast the R&D series for years prior to 2001. The public series consists of estimates of food and agriculturally-related R&D spending by universities, colleges and public research institutions (e.g., the Chinese Academy of Agricultural Sciences, CAAS) as described in greater detail in the Supplementary Material.

The U.S. private food and agricultural R&D series developed by InSTePP and analyzed in Lee et al. (2019) consists of a compilation of data for 466 firms operating in the United States over the period 1950–2014.[5] To be included in the sample, firms were required to have business units that were involved in the manufacture of farm machinery, seed production, or agricultural chemicals (grouped here into an "agricultural research" sub-total) and firms engaged in processing and producing food, beverages, and tobacco products (grouped here into a "food processing research" sub-total). The data are mainly drawn from firm financial filings for food and agriculturally related companies included in Standard & Poor's Compustat (North America) on-line database, supplemented by additional data from company annual reports and various other sources (including R&D estimates for important non-listed companies such as Cargill and Mars). Business segment sales data reported in 10-K filings (collected from either the Security and Exchange Commission's EDGAR database or the Orbis database published by Bureau van Dijk) were used to develop sales data that, when required, were used to estimate the food and agricultural R&D component for firms also engaged in other activities. As Pardey et al. (2019) also describe, sales data by geographical segment were also used to identify the share of food and agricultural R&D conducted in the United States versus elsewhere in the world. It is estimates of spending on private food and agricultural R&D *performed in* the United States for the period 1950–2014 that are reported here.

Comparable *firm-level* data for China are not available. Instead we drew on sub-sectoral aggregates of R&D (and, for years prior to 2001, S&T) spending by industrial enterprises reported in the *China Statistical Yearbook on Science and Technology* for the following sub-sectors: "processing of food from agricultural products," "manufacture of foods," "manufacture of beverage," and "manufacture of tobacco." In

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[4] In contrast to our series, IFPRI's ASTI series ostensibly excludes "off-farm" food processing research (IFPRI 2017b, p. 8). The InSTePP series, inclusive of agricultural and food related R&D, totals 16.7 billion yuan of publicly performed research in 2011, which is still well less than the corresponding public agricultural (nominally exclusive of food) R&D total for ASTI (27.2 billion yuan) (see Figure S3 in the Supplementary Material). For more details on the construction of the InSTePP series see Pardey at al. (2016c).

[5] Fuglie (2016, Tables 1A and B) reports that the USDA, ERS-led database of private sector R&D spending (in the crops, animals and farm machinery sectors) that underpins that paper (and, it seems, Fuglie et al. 2011), includes 324 firms globally, of which only 124 were incorporated in the USA-Canada. Moreover, the 324 global total includes 182 companies that were operating in 2014, and 142 "legacy" companies that operated some time during 1990–2013. For comparison, version 4.0 of the InSTePP private sector food and agricultural R&D database includes 466 firms operating in the U.S. during the period 1950–2014 (with 244 of those firms operating in areas other than food and beverage processing); 322 of these firms (175 in areas other than food processing) operated in the period beginning in 1990, and 131 of those firms were operating in 2014. The implication of these comparisons is that the InSTePP database includes substantially more firms that the USDA database, at least regarding private (food and) agricultural R&D in the U.S.

addition, we included agriculturally-related R&D spending by the "petroleum and chemical" and "machinery" sectors, where the agricultural component was estimated as the share of R&D expenditure for "fertilizer" and "chemical pesticide" within the "petroleum and chemical" sector, and the share of R&D expenditure for "agricultural and garden metal industry," "food, beverage, tobacco and feed production of special equipment manufacturing," and "agriculture, forestry, animal husbandry, and fishery special-purpose machinery and instrument manufacturing" within the "machinery" sector (see Supplementary Material). For some purposes, it would be helpful to segregate the Chinese industrial enterprise data according to firm ownership (i.e., state-owned, privately-owned and publicly-listed shareholding companies) but this was not possible. Instead, in our compilation we follow the OECD (2015, Sections 3.5 and 7.2) statistical guidelines and opted to classify all Chinese industrial enterprises as "private," regardless of their ownership status, since even the government-owned companies largely operate as *private-for-profit* enterprises (Hu et al. 2011), albeit in some cases with access to subsidized credit and bank loans (Fan and Hope 2013; Huang 2010).

Both the U.S. and Chinese R&D spending series were compiled first in nominal local currency units. To account for changes in the price of R&D inputs over time, both these nominal series were then deflated to base year 2011 prices by their respective national implicit GDP deflators taken from World Bank (2017b).[6] Given the relatively lower unit cost of (increasingly equivalent) scientists and other R&D inputs in China vis-à-vis the United States, we used the 2011 purchasing power parity (PPP) from World Bank (2017c) to convert the locally deflated Chinese R&D spending series to an international dollar equivalent that is then directly comparable to the deflated U.S. series.[7]

3. Research spending relativities

3.1. General trends

The case for supporting R&D laid out in *Science-The Endless Frontier*—Vannevar Bush's 1945 report to President Harry Truman—-presaged a surge in U.S. science spending during the post-World War II decades, including spending on food and agricultural R&D. From a (public and private sector) total of $1.1 billion (2011 prices) spent on U.S. agricultural R&D in 1950, real U.S. spending increased to $3.7 billion by 1970 (Fig. 2, Panel a). During the 1950s, total (public and private) investments in food and agricultural R&D conducted in China also began to rise, but from a much lower level—only $0.3 million in 1950 to $44.8 million in 1958—in tandem with an expanding institutional capacity to conduct the research (Fig. 2, Panel a). In 1952, Agricultural Research Institutes (ARIs) were established in seven regions throughout the country, and the central government formed a Coordinating Committee for Agricultural Research in 1957 (Fan and Pardey 1992, Table 10). Two years later, the Chinese Academy of Agricultural Sciences (CAAS) was established and the seven regional ARIs were placed under its jurisdiction.

However, the policy support leading to these institutional innovations soon began to falter. The Great Leap Forward policies launched in 1958 and the Anti-Rightist Campaign of 1959 were highly disruptive. As Fan and Pardey (1992, pp. 30–31) described, many research activities were either curtailed or relocated to rural areas: for example, two-thirds of CAAS personnel and one-third of the research institutes were moved to rural areas or disbanded, only to be returned to their original locations during 1962. In response to the disastrous agricultural performance of the prior three years, in 1963 the Ministry of Agriculture set up a Science and Technology Bureau to foster the development of agricultural science and technology and to promote a recovery in agricultural production. But these initiatives were short-lived. The grass roots populism spurred by the Cultural Revolution (1966–1976) saw many scientists and scientific institutions once again relocated to rural areas. STCMA and STDMA (1989, p.2) report that the CAAS staff shrunk precipitously from 7,500 to just 620 in 1970.

The lost scientific decades of the late-1950s to the mid-1970s had substantive and long-lasting negative consequences for the agricultural sciences in China. In 1978, on the eve of the introduction of the Household Responsibility System that ignited a rapid and sustained resurgence in the growth of Chinese agricultural production (e.g., Lin 1992), China invested just $233 million (2011 prices) in agricultural R&D, still a relatively modest amount even though it constituted a 5.2-fold (inflation-adjusted) increase over the corresponding 1958 total (Fig. 2, Panel a). Notably, the gap between U.S. and Chinese spending on agricultural R&D had widened considerably, increasing from a $1.07 billion gap in 1950 to a $5.21 billion gap in 1978.

Fast forward to 2013—the latest year of comparable data—and the agricultural research relativities are dramatically different. In the United States, the sustained surge in public spending in the immediate post-war decades gave way to public policy indifference as the 20th century drew to a close, and then disinvestment in agricultural R&D (Fig. 2, Panel b) (Pardey and Smith, 2017). After adjusting for inflation, U.S. public sector spending in 2013 had retreated to the (inflation-adjusted) totals that prevailed back in 1998. The biotech boom of the 1990s saw a marked uptick of private investment in life sciences, including food and agricultural R&D, and a surge of acquisition activities that took a hit when the dot com bubble burst. This flurry of mega mergers involves pharma and life science companies looking to realize economies of scale in their R&D activities. Other acquisitions—such as the 1996 merger of Ciba-Geigy and Sandoz that formed Novartis, which in 2000 spun-off its own agro-chemical and genetically modified crops businesses which were combined with AstraZeneca's similar business units to form Syngenta—it seems also envisaged reaping scope economies from integrating health and agriculturally related R&D to tap the innovation potential of the then emergent, new biotechnologies (Fig. 2, Panel c).[8] While total (public and private) U.S. spending has continued

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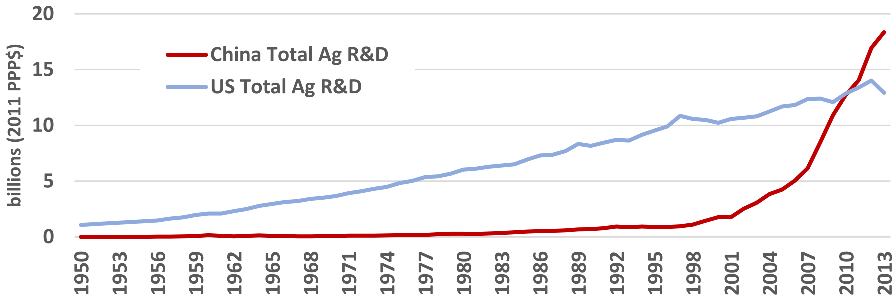
[6] It would be preferable to deflate these series using an index of (agricultural) R&D input prices. InSTePP maintains such a series for the U.S., which reveals that the aggregate price of agricultural R&D inputs rose by 5.04 percent per year for the 1950–2013 period, substantially faster than the corresponding 3.73 percent per year increase in the implicit GDP price index. This is because the salaries paid U.S. scientists (which constitute a large share of overall research costs) has risen much faster than the overall rate of inflation. A similar R&D price index for China is not available.

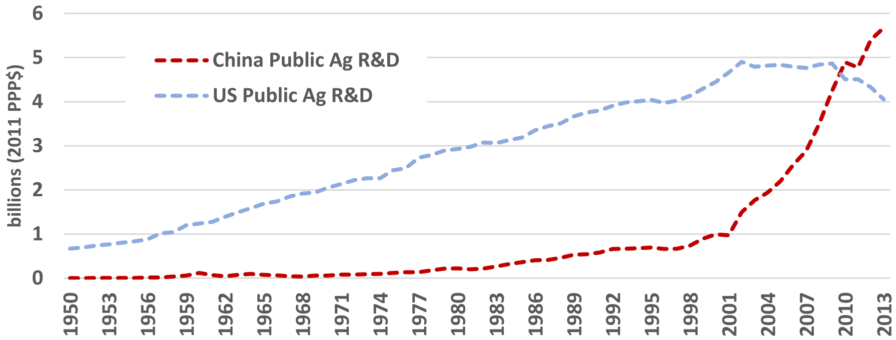
[7] The 2011 PPP was 3.5 yuan per dollar (compared with 6.5 yuan per dollar if market exchange rates were used for the currency conversation). Thus an "international dollar" denominated Chinese R&D spending aggregate (resulting from the use of a PPP) is 184 percent larger than (i.e., almost double) the same aggregate derived using market exchange rates. Notably, using data from the *China Statistical Yearbook* (NBSC, 2015, Table 4–13) we estimate that the average annual wage (inclusive of salary, bonuses, and other fringe, including housing, benefits) of a Chinese scientific research employee (inclusive of all scientific and support staff) in 2011 was Y64,252, compared with a U.S. average (for all scientists and technicians working in life, physical and social science occupations) of $76,140 per scientist (BLS, 2018). If a Chinese and U.S. scientist were deemed of equal quality, this implies a "scientific salary" based PPP exchange rate of 0.844 yuan per dollar. Given the labor intensive nature of R&D (and the particular nature of that scientific labor) this suggests that all the Chinese food and agricultural R&D aggregates referenced and discussed in this paper understate the relative R&D capacity of China vis-à-vis the U.S. when using a conventional GDP-based PPP conversion factor.

[8] For example, in 1985 Monsanto (at the time a chemical company) acquired G.D. Searle (a life sciences company), but in 2002 sold its pharmaceutical business to Pfizer. BASF, a German chemical and biotechnology company, finalized its acquisition of Monsanto on June 7, 2018. Novartis, formed in 1996 by the merger of Geigy, Ciba and Sandoz, then merged with Zeneca in 2000 to form Syngenta, which in 2017 was acquired by China-Chem (minus some key pesticide assets to satisfy regulatory approval).

Panel a: Total (public and private) agricultural R&D spending



Panel b: Public sector agricultural R&D spending



Panel c: Private sector agricultural R&D spending

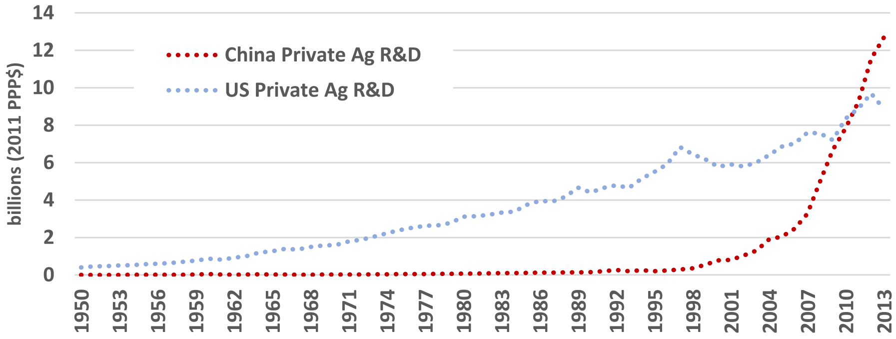


Fig. 2. Public and Private Agricultural R&D Spending in China and the United States, 1950–2013. *Source*: Authors estimates based in sources tabulated in Table S2, Supplementary Material for China and USDA, CRIS (various years) and sources cited in Lee et al. (2019) for the U.S.

to grow, it has been at a much reduced rate: 1.9 percent per year from 2001 to 2013 versus 2.6 percent per year for the prior two decades (1981–2000).

In China, a series of policy initiatives bolstered public and private investments in food and agricultural R&D, especially after 2000. Beginning in the mid-1980s, the Chinese agricultural research system underwent a series of reforms focusing on shifting public agricultural R &D funding more towards competitive grants, encouraging technology transfer to farmers, and enabling the commercialization of research products emanating from public R&D agencies (Huang et al., 2004). The Chinese government implemented a number of policies that included the provision of low-interest loans, subsidies, and various tax incentives designed to encourage companies investing in (agricultural) R&D activities (Fan et al., 2006; Hu et al., 2011; Chen et al., 2017). IPR protection was also strengthened with the promulgation of the Patent Law of the People's Republic of China in 1984 and the passage of plant variety protection legislation in 1997 (Koo et al., 2007; Zhong and Yang, 2007). Private-for-profit companies were gradually allowed entry to agricultural input markets and the food sector in the late-1980s and early-1990s (Hu et al., 2011). Since the mid-2000s, through the establishment of leading enterprises (also known as “dragon-head enterprises,” translated from their Chinese name “long tou qi ye”), the rise of agribusiness nationwide and the entry of urban capital into agriculture has been an increasingly important dimension of agricultural development in China (Zhang and Donaldson, 2008; Zhang et al., 2015).

Since at least 2003, agricultural development was identified as an area of national priority in China’s annual central government No. 1 Central Policy Documents (Zhang et al., 2015). China’s 13th Five Year Plan for 2016–2020 (PRC, 2016) highlighted improving agricultural competitiveness as a key goal for the agricultural modernization agenda. These central government policy incentives have spurred a number of initiatives intended to promote agricultural innovation, increase state investment in agricultural R&D, encourage private agribusiness, and promote agricultural modernization (Zhang et al., 2015).

The radically different spending trajectories plotted in Fig. 2, Panel a—an acceleration of growth in China, and a deceleration in the United States—show that in 2010 China began outspending the United States in total food and agricultural R&D. By 2013, China spent $1.40 on agricultural R&D for every U.S. dollar. Even more dramatically, our new estimates indicate that in 2013 China was spending more on both public ($5.7 billion in China versus $4.0 billion in the United States, see Fig. 2, Panel b) and private ($12.7 billion in China versus $9.1 billion in the U.S, see Fig. 2, Panel c) food and agricultural R&D.

3.2. The privatization of food and agricultural R&D

The private sector has long been a source of significant innovations for U.S. agriculture. As Alston and Pardey (2006, p. 4–22) observed "Among the [private sector] inventors who devised some of the more widely known innovations in U.S. agriculture, we can count Eli Whitney, who patented the cotton gin; Cyrus McCormick, whose mechanical reaper "made bread cheap"; John Deere, whose steel-tipped moldboard plows helped tame the prairies; and Hiram Moore, who built the first combined harvester (combining a reaper and a thresher in one machine). The list of biological innovators is less well known, but the legendary Luther Burbank, who developed scores of new and improved varieties, many of which still bear his name, is representative of thousands of farmer-scientists who by careful selection and, in some cases, hybridization, improved the plant varieties available to American farmers."

From the efforts of these individual innovators, and others, developed long-lived—but in more recent decades merger and acquisition prone—corporations that continue to invest in agricultural R&D such as Deere & Company (brand name John Deere) founded in 1897; Monsanto Company founded as a chemical company in 1901[9]; and DowDupont (formed in August 2017) via a merger of the Dow Chemical Company (founded in 1897) and DuPont-Pioneer.[10] Iconic U.S. food companies with substantive investments in food (and agricultural) R&D include General Mills (founded as the Minneapolis Milling Company in 1856); PepsiCo (formed in 1965 via the merger of Pepsi-Cola Company and Frito-Lay and including Tropicana Products since 1998 and the Quaker Oats Company since 2001); Tysons Foods established in 1935; and the Kraft-Heinz Company formed as a 2015 merger of the H.J Heinz Company (founded 1869) and the Kraft Foods Group, Inc (which had its origins as the National Dairy Products Corporation founded in 1923).

Reforms to the Chinese "science and technology management system" launched in March 1985 spurred efforts to commercialize and increasingly privatize R&D activity throughout the country (Huang et al., 2004; Fan et al., 2006). Public agricultural research institutes established commercial enterprises (not all of whom were related to food and agriculture, and not all of whom undertook R&D) and shareholder companies in the seed, food, chemicals and agricultural machinery markets—many, at least initially, were spun off from development firms founded by public research institutes—, as did state-owned enterprises operating in this same economic space. Multinational agribusiness companies also made (sometimes tentative) R&D moves into China, although incomplete marketing, regulatory, intellectual property rights, and other institutional barriers dampened the inflow of foreign direct investment in the food and agricultural sectors generally, and for R&D in particular, at least in the early phases of the reform (Rozelle et al., 1999; Koo et al., 2006). The benefit-cost calculus of multinational firms conducting R&D within China appears to be changing. In recent years a number of multi-national firms with interests in food and agriculture opened sizable R&D facilities in China, including Hormel Foods (in 2008), BASF (2012), Syngenta (2012), Pepsico (2012), General Mills (2014), and Cargill (2016), although the extent of their spending focused on food and agricultural R&D conducted within China is difficult to discern.[11]

The recent rapid growth in investment in private food and agricultural R&D in China—especially research carried out by state-owned agri-businesses such as the YTO Group (whose holding company is SINOMACH) and its subsidiary China First Tractor Co. Ltd, the agriculture, animal husbandry and fishery company CNDAC (China National Agricultural Development Group Corporation), and the food processing, manufacturing and trading firm COFCO (China National Cereals, Oils and Foodstuffs Corporation), but also privately listed companies such as the WH (formerly Shuanghui) Group (meat and food processing), the Yili Group (milk processing), and the China Yurun Food Group (meat processing)—means that China now also outspends the United States in private food and agricultural R&D.[12] This shifting global balance reflects two reinforcing developments: (1) the accelerating growth of domestic private (state-owned and publicly listed) R&D capacity in China directed to crop genetics, farm machinery, food processing and other relevant business segments, and (2) the relatively recent offshoring of R&D endeavors into rapidly growing middle-income countries by multi-national firms headquartered in the rich countries. Recent takeovers—including the WH Group's purchase of Smithfield Foods in 2013, and ChinaChem's 2017 acquisition of Syngenta AG—are accelerating the privatization of food and agricultural R&D in China.

So, given the continued consolidation among U.S. food and agribusiness over recent decades and the rapid expansion of private activity in China, how have the relative spending trajectories and food versus agriculture composition of R&D fared in these two countries? Both series (see Fig. 2, Panel c) show a distinct but different trend break in the mid- to late-1990s. After an upward blip in private U.S. food and agricultural R&D spending around the mid-1990s, growth slowed dramatically thereafter—6.0 percent per year during the period 1950–1997, versus 2.3 percent per year thereafter to 2013. The scaling back of public spending and the increase in the private share of U.S. agricultural R&D has realigned the respective public–private shares (37.4 percent private in 1950 versus 69.1 percent in 2013) performing agricultural R&D which are now more in line with the compositional structure of overall U.S. R&D spending (where the private share, by performer, averaged 70.7 percent in 2013, little changed from the 70.3 percent share in 1953) (NSB, 2016, Appendix Table 4–2).

In stark contrast, private (including state-owned) agricultural R&D spending growth in China accelerated, with growth in the post-1995 period averaging 23.0 percent per year, well above the 17.9 percent per year for the pre-1995 period. Regarding the public versus private orientation of that spending, Fuglie (2016, p. 35) recently wrote that "[w]ith a relatively low level of private agricultural R&D, agricultural research in China continues to be dominated by public institutes." This contrasts with an earlier article by Hu et al. (2011, p. 416) who concluded "… that while the public sector monopolized agricultural research until recently, private agricultural R&D has grown rapidly since 2000…" Our results reinforce Hu et al.'s findings. Notwithstanding the robust growth in public R&D investment in China over the past few decades, the growth in private research appears to be even more

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[9] In June 2018, Monsanto Company was acquired by Bayer AG, a German chemical, pharmaceutical and life sciences company founded in 1863.

[10] DuPont-Pioneer is established through a 1999 merger between the seed company Pioneer (founded as the Hi-Bred Corn Company in 1926) and the chemical company DuPont (formally E.I du Pont de Nemours and Company, founded originally as a gunpowder mill in 1802). The agricultural assets of DowDupont have been consolidated into a division named Corteva Agriscience, which is slated to spin-off into a standalone company by June 2019 (see www.corteva.com/resources/media-center/corteva-announces-new-leadership-structure.html)

[11] For details on Hormel Foods see www.hormelfoods.com/Newsroom/Press-Releases/2008/02/20080228; BASF, www.greater-china.basf.com/apex/GChina/en/content/BASF-China/1.1_About_Us/About_BASF_in_Greater_China/Research_and_development; Pepsico, www.bloomberg.com/news/2012-11-13/pepsico-opens-china-r-d-center-as-competition-heats-up-with-coke.html; Syngenta, www.syngenta.com.cn; General Mills, http://www.generalmills.com/en/Data/Story-content/Innovation/GeneralMillsChina; and Cargill, www.cargill.com/2016/cargill-opens-innovation-center-in-china.

[12] The official Chinese statistics refer to "industrial" rather than "private" food and agricultural R&D, highlighting the distinctive role of state-owned, for-profit firms in China versus publicly listed shareholding companies in China and the United States. In this paper we use the terms "industrial" and "private" interchangeably.

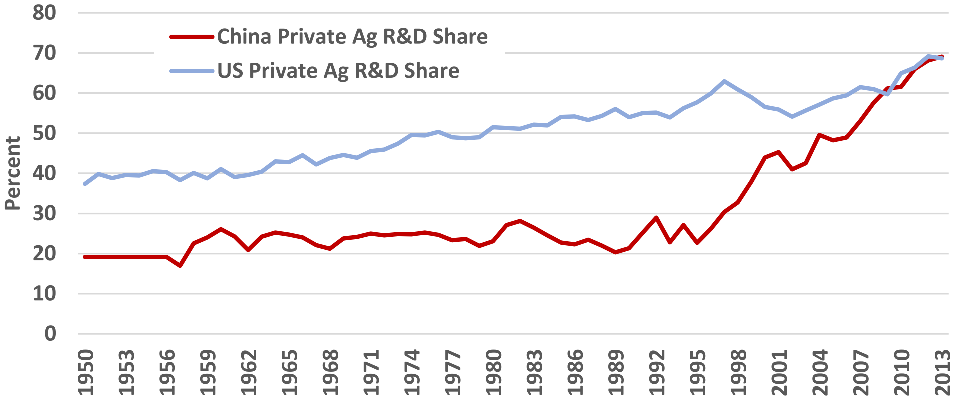

Fig. 3. The Private Share of U.S. and Chinese Food and Agricultural R&D, 1950–2013. *Source*: See Fig. 2.

pronounced so that the share of Chinese food and agricultural R&D conducted by the private sector has grown rapidly since the early 1990s.[13] We estimate that the private (for-profit) share of Chinese food and agricultural R&D averaged 23.8 percent for the period 1950–1999, growing rapidly thereafter to 69.1 percent by 2013, similar to the corresponding U.S. private R&D spending share (Fig. 3).[14]

Not only has the Chinese government put in place a supportive policy environment for increased private participation in the food and agricultural sector (as described above), it also has a heavy hand in the day-to-day operations of enterprises in the agricultural sector regardless of their ownership structure (Waldron et al., 2006). Moreover, the government's firm-level influence in the agribusiness sector is extensive. According to Schneider (2017, p.9), in 2011 China had in excess of 280,000 agri-business enterprises, almost half of which had a national level dragon-head designation along with the considerable state (financial, market, legal) support that comes with such a designation. These private (state and shareholder-owned) dragon-head enterprises have an extensive market reach, impacting around 60 percent of Chinese crop production, 70 percent of livestock (pigs and poultry) and 80 percent of the country's aquaculture production in 2011. While we have no information regarding the R&D performance of specific companies, their sheer economic size suggests they are playing a pivotal part in the rapid rise of the agri-business R&D totals in China.

4. The intensity of food and agricultural R&D

The discussion to date has focused on the magnitude of the absolute investment in R&D. However, larger agricultural economies are likely to invest more in agricultural R&D than smaller economies. Thus, an alternative way of gauging the commitment to agricultural R&D is to compare the amount spent on agricultural R&D *relative* to the amount of agricultural output; known as the intensity of R&D investment.

4.1. Overall trends

Using agGDP—a value-added measure of agricultural output (Fig. 4, Panel a)—, the intensity of U.S. agricultural R&D grew from just 0.8 percent in 1952 to a peak of 9.1 percent in 2002, thereafter declining to 6.1 percent in 2013 (Fig. 4, Panel b). In other words, for every hundred dollars of U.S. agricultural output (agGDP) in 2013, there were $6.1 invested in public and private agricultural R&D carried out in the United States. That same year, China invested just $1.2 in agricultural R&D for every hundred dollars of agricultural output, much smaller than the comparable U.S. figure but well above the 0.2 cents of agricultural R&D spending per hundred dollars of agricultural output in China in 1952 (Fig. 4, Panel b).

The relatively low rate of growth and persistently lower level of intensity of research in China versus the United States seemingly belies the relative rapid growth in spending on agricultural R&D in China versus the United States over recent decades. The answer to this apparent conundrum is that the rapid rate of growth of Chinese agricultural R&D spending (Fig. 2, Panel a) was, until very recently, almost matched by a similarly rapid rate of growth of Chinese agricultural output (Fig. 4, Panel b).[15] Notably, in 1966 China's value-added agricultural output surpassed that of the United States, and by 2013 China's agGDP was 7.2-fold larger than the corresponding U.S. figure. Consequently, although the amount of Chinese agricultural R&D spending is now much larger than in decades past (and, in PPP terms, now surpasses agricultural R&D spending in the United States), R&D spending per dollar of output has not substantially "deepened" or intensified in China over the past 50 years.

4.2. Agricultural R&D growth regularities

How has the relative importance of growth in the intensity of R&D versus growth in the economic size of the agricultural sector varied over time in accounting for the overall growth in agricultural R&D spending in the United States versus China? Applying a log-difference decomposition to the identity $agGERD = agIR \times agGDP$ (i.e., agricultural R&D

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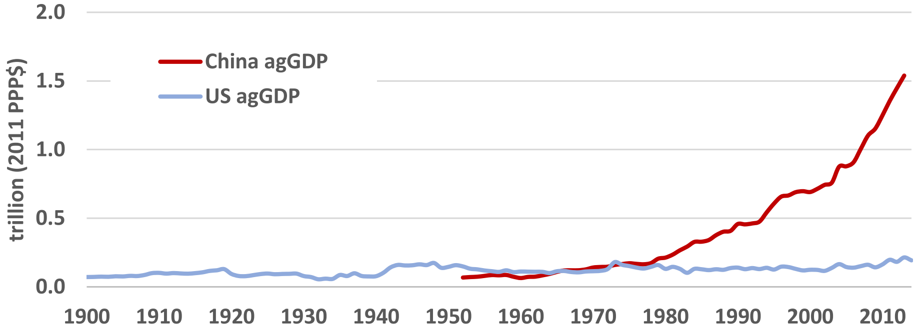
[13] This more recent, phenomenal growth in private food and agricultural R&D in China is consistent with the rapid privatization of the Chinese economy generally, as described and quantified by Lardy (2014).

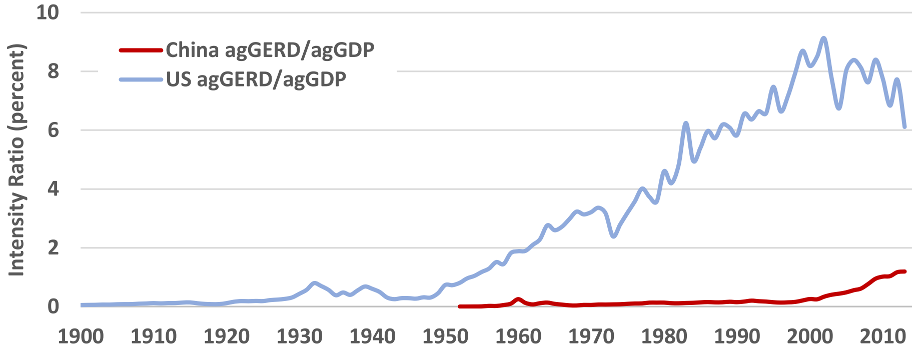
[14] For comparison, Pray et al. (2007, Table 1) report no private food and agricultural R&D spending in China in 1985 (compared with our estimate of $107 million, 2011 PPP prices). This same source also includes a 1995 estimate that can be traced to Pray (2001), who conducted a survey of 27 firms (Pray 2001, Table H-5) and reports a total private-sector R&D spending estimate for China of US$11–16 million (1995 prices using market exchange rates) for circa 1995 (Pray 2001, p. 137) or US$16 million (Pray 2001, Table H-6). The latter figure is equivalent to $64.0 million of food and agricultural R&D spending after adjusting to 2011 prices and converting with a 2011 PPP exchange rate, which is substantially less than the comparable $203 million we estimate for Chinese private-sector food and agricultural R&D spending in 1995. See Figure S3 in Supplementary Material for additional comparisons with other estimates.

[15] The World Bank (2015, p. 88) defines value added output as the net output of an industry after adding up all outputs and subtracting intermediate inputs. There is comparatively little growth in U.S. value added agricultural output (agGDP, or agricultural gross domestic product) over the 1960–2013 period, reflecting the substantial growth in the intermediate inputs required to produce that output (Alston et al., 2010) (Fig. 4, Panel a). Value added agricultural output growth in China is significant, but more muted than the corresponding growth in gross output (21-fold versus 50-fold increase) for similar reasons. The gross (constant-priced) value of agricultural output grew by 2-fold from 1960 to 2013 in the U.S. and 24-fold in China, such that China now produces $7.2 worth of agricultural output (agGDP) for every dollar of U.S. production (Fig. 4, Panel a).

Panel a: Agricultural GDP



Panel b: Agricultural research intensity ratio



Panel c: Agricultural share of GDP

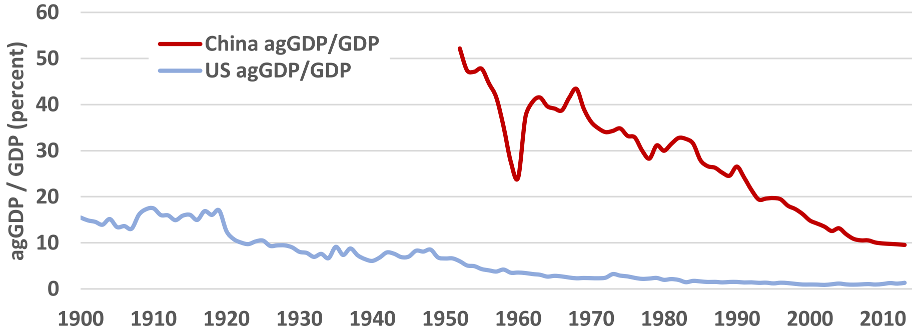


Fig. 4. Agricultural GDP and the Intensity of Agricultural Research in the United States and China, 1950–2013. *Source*: R&D data source same as Fig. 2. U.S. and China agGDP data from 1970 onwards come from United Nations Statistics Division (2016). agGDP series for the U.S. backcast to 1900 using agGDP historical series from BEA (2017) and U.S. Census Bureau (1949). China agGDP series backcast to 1952 using agGDP data from the World Bank (2017a) and NBSC (2005).

spending, *agGERD,* exactly equals the product of the corresponding research intensity ratio, *agIR,* and agricultural gross domestic product, *agGDP*), enables parsing the growth of agricultural R&D into its primary components. Table 1 reveals that almost 64.3 percent of the growth in total (i.e., public and private) U.S. agricultural R&D spending since 1960 is attributable to increasing the intensity of investment in research. Just 35.7 percent of the growth in R&D spending (which averaged 3.5 percent per year) was attributable to expanding the economic size of the agricultural sector. The primary sources of growth in Chinese agricultural R&D spending are very different. Two-thirds of the rapid growth (averaging 8.9 percent per year) is attributable to the growth in agricultural output, while just one third of the R&D growth was associated with an increase in the intensity of R&D spending.

Parsing these growth decompositions into various sub-periods points to differences in the timing of structural shifts in the sources of growth of agricultural R&D spending in China versus the United States. During the first phase of our data, from 1960 to 1999, most (specifically 95.5 percent) of the growth in U.S. agricultural R&D expenditure (averaging 4.1 percent per year) is attributable to the growth in intensity, while the growth in China's agricultural R&D expenditure (averaging 5.6 percent per year) is exclusively attributable to the growth in agricultural output (Table 1). During the latter period, from 2000 to 2013, China experienced a much higher rate of growth for agricultural R&D (averaging 18.0 percent per year), but now only one third of that growth is attributable to the growth in agricultural output with the remaining two thirds being attributable to the growth in intensity. During this latter time period the United States exhibited a much slower rate of R&D growth (averaging 1.9 percent per year) with negative growth in intensity (so that all the growth in R&D spending was attributable to an expansion in the economic size of the agricultural sector).

4.3. *Public vs private R&D intensities*

The intensity of public vis-à-vis private agricultural R&D has evolved in quite distinctive ways, but with notable (and potentially profound) parallels between developments in the United States and China. In 2013, the private sectors were investing more intensively in

Table 1
Sources of Growth in U.S. versus Chinese Food and Agricultural R&D Spending.

		agGDP/ GDP	Rate of Growth of agGDP	Rate of Growth of agR&D	Share of growth attributable to agGDP	Intensity Ratio
		(percent, annual average)	*(percent per year)*		*(percent)*	
All years						
1960–2013	China	25.3	6.0	8.9	67.1	32.9
1960–2013	U.S.	1.8	1.2	3.5	35.7	64.3
Prior 2000						
1960–1999	China	30.1	6.1	5.6	108.8	−8.8
1960–1999	U.S.	2.1	0.2	4.1	4.5	95.5
Post 2000						
2000–2013	China	11.5	6.2	18.0	34.3	65.7
2000–2013	U.S.	1.0	4.2	1.9	215.4	−115.4

Source: Authors estimates based in sources tabulated in Table S2, Supplementary Material for China and USDA, CRIS (various years) and sources cited in Lee et al. (2019) for the U.S. R&D data. See Fig. 4 for source of agGDP data.

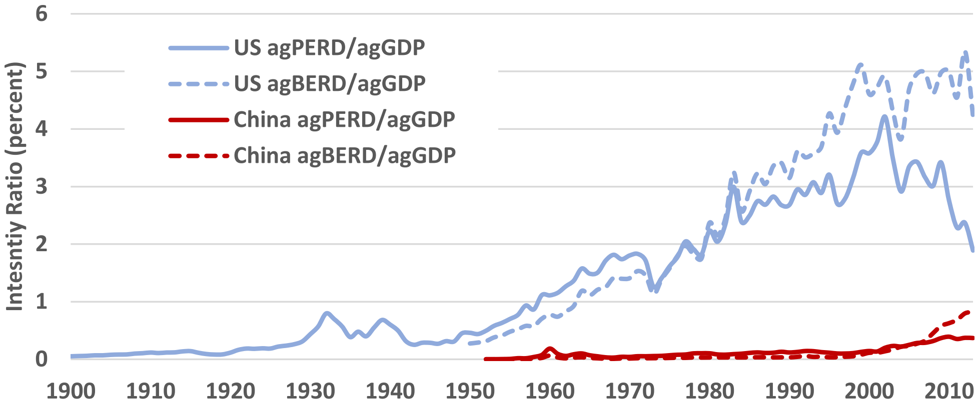


Fig. 5. Private vs Public Agricultural R&D Investment Intensities. *Source*: See Fig. 2.

agricultural R&D than the public sectors in both countries (Fig. 5). In the United States for every hundred dollars of agricultural output the private sector invested $4.2 compared with just $1.9 by the public sector. But this was not always the case. In both China and the United States, public research intensities were higher than private intensities when the overall intensity of investment was comparatively small (cf. Fig. 5 with Fig. 4, Panel a).

However, the situations during which these public-private spending relativities switched varied markedly between the United States and China. In China, private intensities began to exceed public intensities in 2007 when the overall intensity of agricultural R&D spending was just 0.6 percent (and the agricultural share of overall GDP was 10.5 percent). From this perspective, the public-private switch in China occurred much sooner than the corresponding switch in the United States, which occurred in 1980 but not until the overall (public plus private) intensity of investment was much larger, 4.6 percent, and agriculture had shrunk to a much smaller share, just 2.0 percent, of overall GDP (Fig. 4, Panel b).

4.4. On- versus Post- farm private R&D relativities

To assess the relative "agriculture (net of food-related)" versus "food (net of agriculturally-related)" orientation of U.S. and Chinese research it is worth considering some of the market fundamentals that shape these on- versus post-farm R&D relativities. Over the past decade and a half, China's population has rapidly urbanized (from 36 percent in 2000 to 56 percent in 2015, NBSC, 2016). From 2000 to 2015, the per capita incomes of urban and rural households increased 3.6-fold and 3.1-fold, respectively, to 31,790 yuan ($8,463 in 2011 prices) for urban households and 10,772 yuan ($2,868 in 2011 prices) for rural households (NBSC, 2016). Urbanization and income growth in China has spurred marked changes in the structure of consumption, including increased consumption of animal products, snacks and food-away-from-home (Ma et al., 2006; Zhou et al., 2012; Zhai et al., 2014; Jiang et al., 2015). These dramatic developments, along with major improvements in rural transportation logistics among other factors, have rapidly reshaped Chinese agricultural supply chains. This is particularly evident in the breath-taking pace at which food sales in China have moved from informal to much more formal, typically supermarket, outlets. Reardon et al. (2003) reported that the supermarket share of Chinese urban food markets had grown from 30 percent in 1999 to 48 percent just two years later, in 2001, and was spreading rapidly beyond the larger cities to smaller towns and more remote areas in the northwest, southwest and interior of the country.[16] Diaz et al. (2012, Exhibit 1) report that supermarket (and similar) sales accounted for 62 percent of all (urban plus non-urban) grocery sales by 2011.

As food and agricultural supply chains become increasingly (often vertically) integrated, this has economic implications for the incentives to innovate and the nature and pace of innovations in these two sectors (Alston et al., 1995; Swinnen and Kuijpers, 2017; Zilberman et al., 2019). In particular, the integration of these supply chains can influence the relative size of the on- versus off-farm benefits from R&D, with direct implications for the balance of on-farm (agricultural) versus post-farm (food processing) research effort that is likely to be economically attractive (Alston et al., 1995).

An indication of the on-farm versus post-farm value of food and agricultural sales for China versus the United States is given in Fig. 6, Panels a and b. The China data represent sales (or more specifically, a gross industrial output, GOI, value series reported by the National Bureau of Statistics of China) differentiated into on-farm sales from firms selling farm-related inputs (such as agriculturally-related chemicals or machinery inputs) and post-farm sales from firms selling food, beverages and tobacco products. The U.S. data represent the total value of sales, similarly split between the farm-input and food sectors, reported by the same farm input and food processing firms used to compile the corresponding U.S. private R&D data discussed here and in more detail by Lee et al. (2019). The Fig. 6, Panel a China-versus-U.S. sales trajectories are qualitatively similar to the respective agGDP trends plotted in Fig. 4, Panel b. Fig. 6, Panel a, shows China's total (farm-input and

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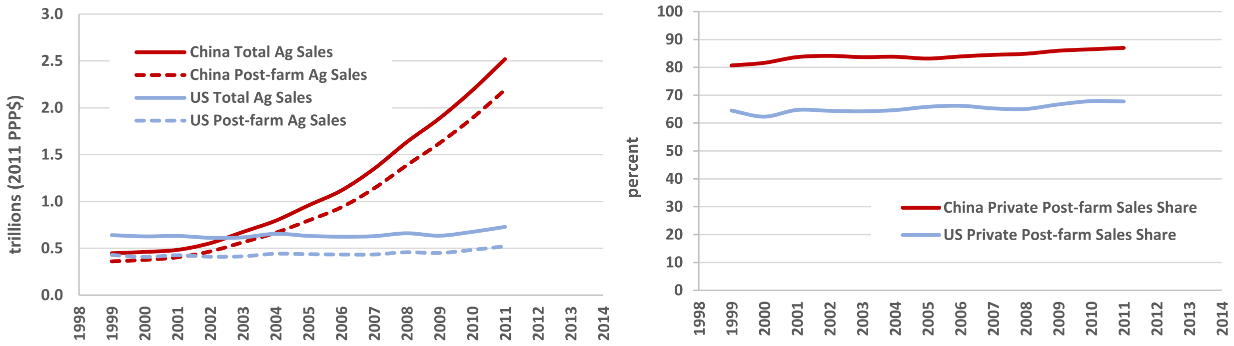
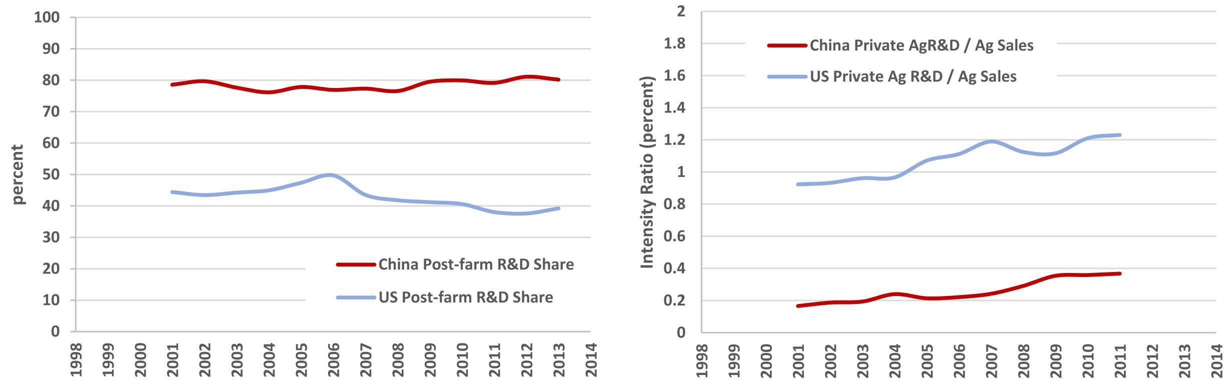
[16] Reardon et al. (2003, p. 1,142) estimated that the 48 percent urban share was roughly equivalent to a 20 percent supermarket share of total sales, and also noted that the corresponding U.S and French shares were in the 70–80 percent range around that time.


Panel a: Total and post-farm agricultural products sales

Panel b: Private post-farm sales share


Panel c: Private post-farm R&D share

Panel d: Private Ag R&D intensity

Fig. 6. Private On-farm and Post-farm Agricultural Production and R&D Spending in the Private Sector. Source: R&D data source same as Fig. 2. Industrial output data from NBS (various years) for China and sources cited in Lee et al. (2019) for U.S. value of sales data.

food) sales surpassing U.S. sales in 2003 and by 2011, China's sales were 3-fold larger than the United States.

Notably, and perhaps somewhat surprisingly, Fig. 6, Panel b, shows that a larger share (averaging 84.1 percent for the period 1999–2011) of China's total sales are in the post-farm (food processing) sector, relative to the United States, whose corresponding post-farm share averaged 63.4 percent. This may reflect two factors. First the timing of China's transition from informal or traditional food retailing markets to more formal, supermarket style sales indicates that China's supply chain structures were rapidly converging to parity with those in the United States, thus likely inducing commensurate (private sector) attention to R&D activities in these post-farm (food processing) markets. Second, while China's use of improved seed, chemicals and machinery inputs has taken off in recent decades, the available evidence suggests that purchased (seed, fertilizer, herbicides, energy and so on) inputs as a share of the total costs of farm production have historically been lower in China than the United States.[17] Taken together these underlying economic realities are consistent with the China versus U.S. sales share relativities reported in Fig. 6, Panel b. Moreover, they also give support for the on-farm versus post-farm private-sector R&D relativities for China and the United States reported in Fig. 6, Panel c. Finally, Fig. 6, Panel d shows that the private intensity of food and agricultural R&D in China and the United States is increasing over time, but China still lags well behind the United States. There are grounds to expect that China's private investments in food and agricultural R&D will continue to grow as the intensity of its private investments increases.

5. Prospective food and agricultural R&D futures

These new data reveal seismic shifts in the food and agricultural R&D spending relativities of the United States versus China. What might they portend for the future of the relative agricultural innovation capabilities of both countries? In the discussion above, we reveal regularities in the patterns of change in U.S. versus Chinese food and agricultural R&D spending that point to the future prospects of food and agricultural R&D in both countries. In summary, we observe that (a) there is a general tendency for the intensity of food and agricultural R&D to increase as the agricultural share of GDP shrinks, (b) the United States appears to have reached food and agricultural R&D satiation (in that the growth in intensity of food and agricultural R&D has been slowing since the 1980 s, and stalled since the 1990s, Fig. 4, Panel b)—a pattern that Dehmer et al. (2019) observed more generally regarding GERD (gross domestic expenditure on research and development) intensities—, and (c) over time, but only up to a point (and perhaps just for a period in the "development life cycle" of the food and agricultural sectors), the primary source of growth in R&D spending shifts from an expanding agricultural economy, to a deepening or intensification of investments in agricultural R&D. To further explore the relationship between a country's agricultural share of GDP and its intensity of food and agricultural R&D spending, we juxtaposed a scatterplot of the data for these two indicators for both China and the United States against similar data for two additional Asian countries, Japan and Republic of

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[17] For example, the data underlying Alston et al. (2010, Figure 3–15) indicate that for U.S. agriculture, expenditure on material inputs (i.e., purchased seed, fertilizer, farm chemicals. energy and so on) as a share of total costs were 34.7 percent in 1978, increasing steadily to 38.4 percent by 2002 (and averaging 37.2 percent over the period). Roughly comparable cost share data for Chinese agriculture compiled from NDRC (2007) indicate the materials cost shares—including seeds, fertilizer, farm chemicals, plastic films, energy and services, but, notably, for comparability reasons, excluding the costs of tools, machinery rentals, repair and maintenance, and other indirect expenses (such as asset depreciation, taxes, and insurance, etc) that are typically included in reported Chinese cost totals—were 31.4 percent in 1978, dropping to 27.1 percent in 2002 as labor costs began to rise (and averaging 31.8 percent over the entire period).

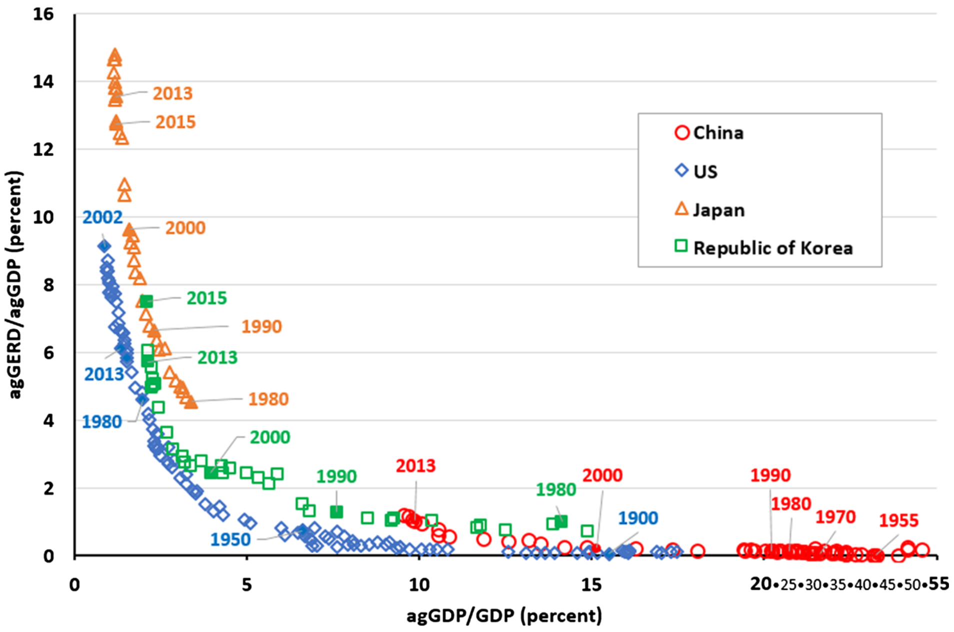

Fig. 7. Agricultural R&D Spending Regularities in China, U.S., Japan and Republic of Korea, 1950–2015. *Source*: China and U.S. data source same as Fig. 4. Japan and Republic of Korea data are from InSTePP International Innovation Accounts Version 3.5. *Note:* Data coverage varies by country: China 1950–2013; U.S. 1900–2013; Japan 1980–2015; Republic of Korea 1980–2015. On the x-axis, when the agGDP/GDP ratio for China exceeded 20 percent it was rescaled to improve the legibility of the figure.

Korea (Fig. 7).

Fig. 7 reveals a remarkable, long-run regularity in the series among all four countries, whereby the intensity of food and agricultural R&D spending increases in a systematic way as the agricultural share of the overall economy (i.e., the agricultural GDP to GDP ratio) declines. Around 2000, the growth in China's intensity of investment in agricultural R&D begun to accelerate, but in absolute terms China's current intensity still remains well below 1.5 percent, making it comparable to the U.S. intensities of the 1950s and the 1980s Korean ratio. Strikingly, there is evidence of a threshold effect in Fig. 4. In the United States, when the agGDP/GDP ratio fell to nearly 5 percent the intensity of (public and private) investment in food and agricultural R&D began to take off. The figure suggests a similar take-off phenomenon in the Republic of Korea, perhaps beginning when the agGDP/GDP ratio approached 10 percent. It appears a similar phenomenon is in its early stages regarding the intensity of Chinese investment. Post take-off, the measured intensity of investment in food and agricultural R&D peaked in 2002 (at 9.1 percent) for the United States, 2009 (14.8 percent) for Japan, and 2015 (7.5 percent) for the Republic of Korea.

Looking ahead, if the empirical regularities in the agGDP shares versus R&D intensities noted above persist, we would expect the growth in investment intensity in Chinese food and agricultural R&D to continue increasing if not accelerating over the decades ahead, and become a more dominant source of growth in the country's agricultural R&D spending. However, it is unclear which particular path China will take as it intensifies its food and agricultural R&D spending. A host of public policy and private choices (including shifts in the pattern of demand for food and agricultural output, domestic and foreign capital investment decisions, and global trade trends) will shape the Chinese intensification trajectory. Nonetheless, given China's agricultural economy is much larger (and still growing much faster) than the U.S. agricultural economy, the empirical realities of the agGERD identity defined above suggest that China's investments in agricultural R&D are on track to substantially eclipse the corresponding U.S. investment in the decades ahead and become a dominant investor in food and agricultural research globally.[18]

6. Conclusion

In this paper we reveal profound shifts in the spending relativities between the public and private food and agricultural sectors within both China and the United States, and between the countries themselves. Specifically, our newly compiled data reveal that China is now spending more than the United States in both public and private food and agricultural R&D on a purchasing power parity basis. Furthermore, the private share of food and agricultural R&D spending in China is now comparable with the corresponding private share in the United States. However, in the United States private spending is roughly evenly split between on-farm versus off-farm R&D, whereas our estimates indicate that in China the private sector spends around four times more on post-farm R&D than it does on research related to on-farm factors.

Looking ahead, the continuation of a rapid growth in spending on food and agricultural R&D in China, increasingly propelled by an intensification of R&D, if the cross-country trends we observed are an indication of China's future, looks likely. This will surely have a significant impact on the performance, competiveness, market structure and resource use of China's food and agricultural sector. Of course R&D spending relativities are but one indication of the relative innovation potentials of these two countries, which in large part reflect the relative intellectual and institutional research capital that each country has accumulated over the years. Moreover, these changing R&D spending relativities themselves reflect a complex combination of policy decisions (and their implementation) and more fundamental market forces. Without question, the contrasting decisions of U.S. versus Chinese policy makers regarding investments in public agricultural R&D—with the United States scaling back public investments and the Chinese doubling down during the past few decades—have magnified the rise of agricultural R&D spending in China vis-à-vis the United States.

But it appears that the passing of the agricultural R&D buck from the United States to China, which our new data reveal is presently in play, are to a significant extent driven by fundamental, longer-run economic forces. Over time these fundamentals will likely continue to fuel the relative rise of agricultural R&D in China, thus contributing to a further realignment of the global geography of agricultural innovation in the decades ahead. This global realignment in R&D spending may well have substantive consequences for the size, shape and accessibility of the global stocks of scientific knowledge that underpin food and agricultural sectors worldwide.

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[18] Using a more formal empirical projections model, Dehmer et al. (2019) similarly conclude that China's investment in overall R&D (GERD) will dominate the projected U.S. investment in the years ahead; specifically a midline projection of \$1.96 trillion (2009 PPP prices) for China in 2050 versus \$0.98 trillion for the United States.

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Declaration of Competing Interest

The authors declare no competing financial interests.

Appendix A. Supplementary material

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