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ARTICLE

Investments in agricultural research and development: recent transformations in Brazil

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Abstract

The article explores changes in volume and composition of investments in agricultural research and development (agricultural R&D) that have taken place in recent decades. It reviews the international experience and presents stylized facts about the groups of developed and developing countries. From an unpublished database of primary data, the study evaluates the dynamics of private R&D investments allocated in Brazil by companies from the agricultural input sectors. The aim of this work is to describe the recent transformations of agricultural R&D efforts in the country and to contribute with decision making processes for agricultural technological progress. The conclusions highlight the high technological intensity, the growth of private investments and the small relative participation of national companies in the technological progress of agricultural input industries in the country.

Keywords | Research and Development; Private Investments; Agricultural Input Firms

JEL Codes | D22; O30; O32; Q16

Investimentos em pesquisa e desenvolvimento agrícola: transformações recentes no Brasil

Resumo

O artigo explora mudanças no volume e na composição dos investimentos em pesquisa e desenvolvimento agrícola (P&D) que ocorreram nas últimas décadas. Para isso, é feita uma revisão bibliográfica da experiência internacional e apresentam-se fatos estilizados dos grupos de países desenvolvidos e em desenvolvimento. A partir de uma base inédita de dados primários, o estudo avalia a dinâmica dos investimentos privados em P&D alocados no Brasil por empresas dos setores de insumos agrícolas. O objetivo do trabalho é descrever as transformações recentes no país e contribuir para a tomada de decisões para o progresso tecnológico da agricultura. As conclusões destacam a alta intensidade tecnológica, o crescimento dos investimentos privados e a pequena participação relativa de empresas nacionais no progresso tecnológico de insumos agrícolas.

Palavras-chave | Pesquisa e Desenvolvimento; Investimentos Privados; Empresas de Insumos Agrícolas

Códigos-JEL | D22; O30; O32; Q16.

1. Introduction

In the last decades of the 20th century and the beginning of the 21st, there has been a renewal of interest on the agricultural development process, which regained a prominent place in multidisciplinary academic debates and political discussions. Projections of population growth, questions about the limits to productive intensification and a search for healthy and safe foods opened the way for studies in different knowledge areas, which were guided by the flaws of the traditional paradigm of agricultural development established by the Green Revolution. Concrete phenomena such as the irrational exploitation of environmental resources, the increase in obesity rates and the persistence of rural poverty in several regions are examples of negative results that have encouraged a reframing of the objectives of agricultural development in society.

Alongside the transformation of the development paradigm, agricultural R&D activities have undergone changes on a global scale. According to Spielman and Ma (2016), in the period of the Green Revolution, investments were concentrated mainly in public research organizations and in the search for production gains in specific food crops. On the other hand, in the period covered by the present study, a greater participation of private companies and an expansion of the objectives pursued in agricultural R&D programs were observed. Activities that seek solutions for "on-farm" productivity gains began to be carried out mainly by private companies. In the same sense, Renting *et al*. (2009) state that the "one size fits all" type of agricultural research system no longer seems appropriate to capture the multiple functions of the sector in society.

In fact, recent changes in agricultural R&D investments have been the subject of a vast and growing literature (PARDEY; ALSTON; PIGOOT, 2006; NASEEM; SPIELMAN; OMANO, 2010; KALAITZANDONAKES *et al*., 2018). Research consensually confirms that there is an ongoing structural change in the knowledge bases and in the regional distribution of activities. Autonomous scientific advances, the liberalization of agricultural markets and the strengthening of intellectual property in developing countries are recurrently pointed out as determinant factors for new configurations (FUGLIE, 2016; PRAY; FUGLIE, 2015). As a result, we can see the acceleration in the pace of innovation deployment and the intensification of competition between companies in the input industries.

In the Brazilian case, works on this topic attest to the growth of public investments in agricultural research along the 2000s and the beginning of the 2010s

(BATALHA; CHAVES; SOUZA FILHO, 2009; VIEIRA FILHO, 2012; STADS *et al*., 2016). However, little is known about the evolution of private investments in the country. This is so because the most recent quantitative analyses on the topic reflect the economic and technological structure of the early 1990s. Roseboom (1999) and Beintema *et al*. (2001) can be identified as state-of -the-art studies in relation to the estimates of private investments in agricultural R&D in Brazil. Since then, countless institutional, technological and economic changes have profoundly impacted the national markets and transformed the agricultural R&D activities carried out in the country.

The main objective of this article is to investigate the structure and dynamics of private investments in agricultural R&D in Brazil, in the period from 1995 to 2012. For such, the study evaluates primary data collected via structured interviews with representatives of leading companies in the agricultural input sectors of the national economy. As it will be seen, from 1995 to 2012, private investments in agricultural R&D in Brazil increased by approximately 450%. It is important to emphasize that the Brazilian agribusiness underwent structural transformations in the same period, such as a diffusion of genetically modified crops, an increase of agricultural credit for the acquisition of inputs, a strengthening of competitiveness and a significant expansion of its cultivated area. Thus, multinational companies producing seeds, agrochemicals, machinery and implements began to have Brazil as one of its main global markets.

The present study seeks to provide elements to answer the following questions: how did the allocation take place and what were the results of private investments in agricultural R&D in Brazil from 1995 to 2012? In which activities of the innovation process in the country did companies concentrated their R&D efforts? What were the main sources of resources that financed investments? Did private research in Brazil accompany the transition in knowledge bases observed in other countries? And regarding the public sector, how did its performance impact private investment decisions in the country?

We intend to contribute to investigations on the Brazilian agricultural research, having as main references the works of Bonelli and Pessôa (1997), Salles Filho and Bin (2014) and Lopes (2012). It is worth noting that this paper primarily highlights the R&D investments made by private companies with no intention to exhaust the subject. Since the growing importance of private R&D does not automatically imply the reduction of the role of public organizations, but rather the search for the most efficient type of participation. Largely, the study aims to provide useful elements for the design of mechanisms to stimulate the technological progress of agriculture.

After the introduction, in the second section, we discuss central points of the theoretical framework that permeates the entire study. To this aim, a bibliographic review is carried out in the field of the economics of agricultural research, calling to mind the evolution of its main research lines and methodologies. We present and discuss results of previous research that support the hypothesis of the strengthening of developing countries in the global agricultural technological progress. The section emphasizes the relevance of studies, like the current one, which transform primary information into economic data. According to Gardner (1992), neglecting research imbued with this purpose hinders the empirical validation of theories, the construction of conceptual models, and threatens science itself.

The third part of the article exhibits the methodology and discusses aspects of the questionnaire used in the interviews. The section discloses the results of the R&D investments made by the sample companies that participated in the study. We intend to highlight the relevance of these companies for the Brazilian innovation in agriculture.

The fourth subdivision of the article evaluates the information collected from the interviews and presents the main results achieved by the study. Quantitative and qualitative data are interpreted in the light of works in the economics of agricultural research employed in the theoretical framework. Contrary to common sense, the research provides elements to reject the argument that frames the Brazilian agricultural sector in the category of low technological intensity. This is because the sectors of agricultural machinery, seeds and biotechnologies have recorded rates of R&D spending which are similar to those of the high and medium-high technological intensity groups in the national industry. In addition, all the sample companies declared that they had introduced at least one innovation in the period and, together, filed approximately 9,500 patents in Brazil's National Institute of Industrial Property (INPI).

The fifth section is devoted to the evaluation of technological progress in the target sectors of the study. The method employed consists in the identification of the technological subclasses[1] which gained or lost relevance in patent applications made by the sample companies in Brazil between 1995 and 2012. This exercise allows positioning the Brazilian case in respect to the global transformation of private

1 The technological subclasses are identified by the four-digit selection of the International Patent Classification (IPC).

R&D activities, materialized in the substitution of investments in technologies with chemical and mechanical knowledge bases by biology-based inventions connected with information, communication and automation technologies. Finally, the conclusion consolidates the main results achieved and points to future developments and studies on the subject.

2. Economics of investment in agricultural research

Investment in agricultural research is one of the main factors responsible for increasing agricultural productivity, and increasing agricultural productivity has significant impacts on economic growth, poverty reduction and food security. As Vieira Filho and Silveira (2016) indicate, the agricultural sector is able to generate technical progress and added value, as well as promote the development of agro-exporting regions. In other words, the impacts caused by the diffusion of modern agricultural inputs, such as high-yield crops and tractors, have transformed agriculture and contributed to the development of regional economies. Since then, researchers have endeavored to measure and evaluate economic, social and environmental returns of agricultural R&D investments. Such issues are recurrently treated on the theoretical framework identified by the field of the economics of agricultural research, which, according to Griliches (1979), started in the 1950s, with the work of T. W. Schultz, who analyzed the impact of technological changes on the input-output relations of the U.S. agriculture and the return on investments that gave rise to new technologies.

Pardey, Alston and Ruttan (2010) indicate that models of partial equilibrium in commodity markets are the most used to investigate the economic impacts of investments in agricultural research. In the original basic model, the benefits of research are evaluated using Marshallian measures of changes in the economic surplus, induced by the diffusion of new technologies. In this context, Nin-Pratt and Magalhaes (2018) make a systematic bibliographic review of quantitative studies that evaluated the return on investment in agricultural R&D.

By and large, impact assessment exercises prove that investments in R&D produce positive economic returns, materialized in supply increases and reduction of prices of agricultural products. However, the assessment of benefits may be affected by theoretical and methodological complications that require extensions to the basic Marshallian model. For example, the assumptions of the basic model do not consider market failures in the appropriation of investment returns, which can result from technological spillovers, non-competitive market structures, the presence of proprietary rights or the time required for R&D investments to yield monetary results.

According to Alston *et al*. (2009), the evolution of this field of investigations aimed to address the failures on the attribution of results, raising questions about the distribution of investment benefits between different stakeholders, in a search for data, measures and methods to gauge impacts beyond economic indicators and in discussions about the meaning of results obtained. It is worth noting that the contributions to the subject of agricultural research relate to a broad literature, unrestricted to the neoclassic framework of the economics of production, covering studies in the economics of development, industrial organization, economic history, political economy, among others.

Studies in the field of the economics of agricultural research have a long tradition in Brazil. This fact is said to be consistent with the relevance of the sector in the science and technology activities carried out in the country. Alves (1968) adopted the economic surplus model in his master's thesis to evaluate the economic impacts of an agricultural extension program in Minas Gerais. The article of Ayer and Schuh (1972) is the first scientific paper published in an international journal that evaluated the impacts of investments in agricultural R&D in Brazil. The authors estimated an internal rate of return on investment of approximately 90% in the improvement of cotton varieties in the state of São Paulo. That is, out of each 1 monetary unit invested, 1.9 returned to the Brazilian society. In addition, their work provided original contributions to the international discussion, proposing theoretical and methodological extensions to evaluate the distribution, across different stakeholders, of the costs and benefits of investments.

Avila, Rodrigues and Vedovoto (2008) traced an extensive bibliographic review of assessments of the economic impact of agricultural research in Brazil. As the authors highlight, the evaluations carried out by Embrapa (the Brazilian Agricultural Research Corporation) employed several methodological approaches – econometric models based on the productivity function, decomposition models, total productivity indexes, systems of equations – but emphasized the use of the concept of economic surplus. Avila, Rodrigues and Vedovoto (2008) expanded the scope of assessments in Brazil with the development of methodologies and specific conceptual bases for the analysis of social, environmental and political-institutional return on investment in R&D carried out by Embrapa.

Alston *et al*. (2009) emphasize that part of the literature of the economics of agricultural R&D includes studies describing, documenting and quantifying the investments of institutions that fund, regulate and conduct research. For the authors, assessments of the relationship between investments in research and gains in agricultural productivity depend on the work of researchers who collect data from inputs and outputs of knowledge production. Thus, studies to access, group and disseminate primary information about investments in agricultural R&D are valuable on their own, as they require a great effort to search and interpret data which are difficult to obtain, and which comprise information that is necessary for other types of approaches in the field of the economics of agricultural research.

Nevertheless, Pray and Fuglie (2015) emphasize that it is common to find approaches which inaccurately portray the way that private companies operate in the technological progress of agriculture. According to the authors, the private R&D in agriculture described by the Frascati Manual (OECD, 2002), and reproduced extensively in discussions on sectoral technological intensity, is limited to investments made by companies in which the production of commodities represents either most of the value added or sales, e.g., seed multiplication companies. R&D investment made by companies that develop and manufacture knowledge-intensive products, such as improved cultivars, biological control products, agricultural machinery and implements, information technologies, agricultural biotechnologies and animal health, is accounted for in the manufacturing industry, even if all innovations are used in agricultural production.

Empirical inaccuracy downplays R&D investment in agriculture and serves as a basis for distorted analysis of the technological content of the sector, regularly treated as of low technological intensity. Low-technology sectors can be overlooked in governmental actions to encourage an increase in R&D investment. Therefore, the survey and disclosure of private R&D expenditure classified by socioeconomic objectives, which are carried out in this work, are indispensable elements for the proper representation and strengthening of agricultural technological progress.

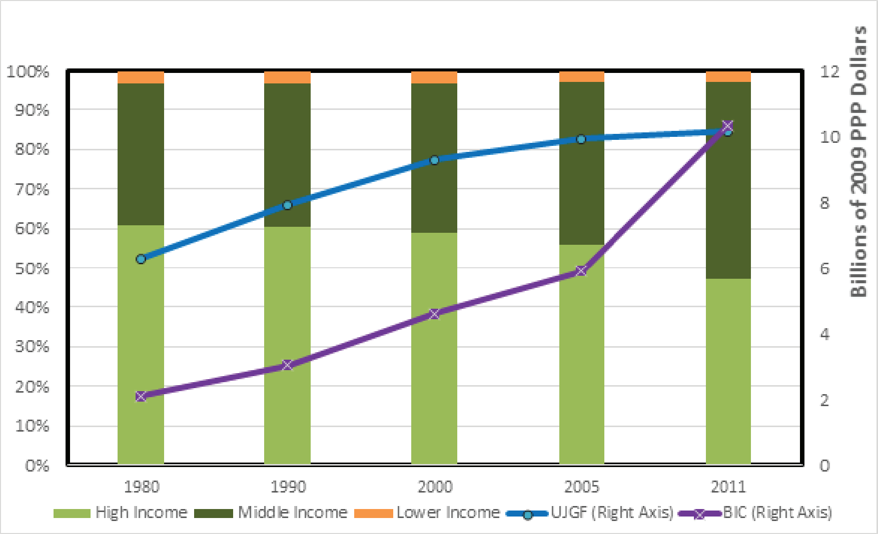
2.1 Recent evolution in agricultural research investments

According to Alston, Pardey and Smith (1998), since the end of the 1970s, a significant group of countries has made changes in the funding and institutional environment of agricultural public research, as well as in incentives to private expenditure. The change in approach on the participation of the state in the economy, formalized years later by the guidelines established in the Washington Consensus, constituted the initial background for the transformations that were intensified after the great 2008 recession.

Specifically in developed countries, the 1980s marked the beginning of a long period of stagnation of public investment and growth of private investment in agricultural R&D. In some countries of this group, such as the United Kingdom, Australia, New Zealand, the Netherlands and Canada, the last decade has seen an absolute reduction in government investments and accelerated growth of private expenditure. Conversely, developing countries have recorded constant elevations in investments in both institutional spheres.

Figure 1 shows the evolution of public investments in agricultural and food R&D from data compiled from database of the International Science & Technology Practice & Policy (InSTePP[2]). Note that, in 2011, for the first time in history, governments of developing countries invested higher values than those observed in developed countries. In particular, as stated in Figure 1, public efforts in agricultural R&D in Brazil, India and China (BIC) exceeded all the expenditure observed in USA, Japan, Germany and France (UJGF). However, per capita spending still grants a great advantage to developed countries. It is worth noting the relative stagnation of underdeveloped countries, which did not exceed the mark of 3.5% of the total of global public investments in agricultural and food R&D in the period under scrutiny.

FIGURE 1
Public investment in agricultural R&D
Brazil – 1980-2011



Source: Pardey *et al.* (2016).

2 Available in: http://www.instepp.umn.edu/.

Concomitantly with the reduction of public investments, there was an intensification of the search for these resources – which began to be disputed among a larger number of research agendas – in developed countries. This happened because interest groups that do not represent farmers gained greater importance in formulating policies for agriculture. Food processors, consumer groups, environmentalists and conservationists have taken on relevant roles, diluting the power of farmers and public research organizations on decisions about the allocation of public investment. In the case of the US, Fuglie and Toole (2014) point out that less than 40% of the public investment in agricultural research in the last decade was applied to activities for "on-farm" productivity gains. In this context, private companies have become the leading innovation providers focused on agricultural productivity gains.

Effectively, Pray and Fuglie (2015) indicate that the participation of private investments in the worldwide total increased from 36% in 1980 to 44% in 2009. Specifically in developed countries, private spending on agricultural R&D exceeded the amount of public spending, mainly due to the weight of investments made by the leading global companies of the agricultural input industries. Fuglie, Clancy and Heisey (2018) point out that, in 2011, approximately 85% of private investments in agricultural R&D in the world were carried out by companies controlled by capitals based in developed countries. Notwithstanding, increasing amounts of these resources have been allocated in developing countries, in a process led by companies seeking to broaden the internationalization of their R&D activities. In the Brazilian case, investments in subsidiaries or joint ventures controlled by international capital have been a successful business strategy for internalizing and appropriating knowledge that had been accumulated over decades of public investments in tropical agriculture research.

Primary data released by Pray and Nagarajan (2014) show that the private spending on agricultural R&D in India surged from US$ 24 million in the mid-1980s to US$ 250 million in the 2008/2009 harvest. The study made by Hu *et al.* (2011) shows that private investments in China increased fourfold from 2000 to 2006, reaching a total of US$ 438 million. In the Brazilian case, private expenditures in agricultural R&D jumped from US$ 75 million to US$ 394 million from 1995 to 2012. Transnational investment from companies based in developed countries represented a significant portion of the private R&D increments observed in Brazil.

Considering the relevant role of international technological spillovers and the persistence of low public investment in underdeveloped countries, questions emerge about the role of developing countries in the global growth of agricultural production and productivity. Are Brazil, China and India willing to transfer knowledge and technology to the most vulnerable regions free of charge, in the form of international aid, especially in a scenario of intensifying competition in the international market for agricultural products? Beyond commercial strategies, issues of this type reflect concerns about food security and serve as a starting point for future studies.

3. Research methodology

The initial motivation for this research was the limited availability of information on R&D investments made by knowledge-intensive private companies in Brazil. In fact, the innovation survey of the Brazilian Institute of Geography and Statistics (PINTEC/IBGE) discloses disaggregate information only for R&D investments by companies in the agricultural machinery and implements sector. We believe that the present work fulfills its main objective, which is to broaden the access to information on the technological progress of agricultural input industries. It is important to emphasize that the initial demand for this study arose from a flagrant dissatisfaction with the results of the survey of global expenditure on agricultural R&D disclosed by Fuglie *et al*. (2011), especially regarding private investments in developing countries.

The work began with the transfer, by the Economic Research Service of the Department of Agriculture of the United States (ERS/USDA), of basic information related to our research project, such as a questionnaire and contacts of representatives of companies in Brazil, deadlines, objectives and expected results. After that, we proceeded to select the sample companies, which were contacted to take part in structured interviews, which were based on the questionnaire obtained from the ERS/USDA. The criterion used for the selection of companies was their having relevant participation in the total revenue of the sector or in the registration of new products and patents in the country.

The information related to the registration of new products in the seed and agrochemical sectors was obtained, respectively, in the CultivarWeb system[3] and in the technical information on the registration of agrochemicals and related products[4], which constitute open databases under the responsibility of the Brazilian Ministry of Agriculture, Livestock and Food Supply (MAPA). The information used as proxy

3 Available in: http://sistemas.agricultura.gov.br/snpc/cultivarweb/cultivares_registradas.php

4 Available in:http://www.agricultura.gov.br/assuntos/insumos-agropecuarios/insumos agricolas/agrotoxicos/informacoes-tecnicas

for innovation efforts in the agricultural biotechnology sector was the registration of plants for commercial use and planned release in the environment (LPMA), disclosed by the Brazilian National Technical Biosafety Committee (CTNBio). In the agricultural machinery sector, sample companies were selected based on data from the production and sales of wheeled tractors and harvesters, available in the annuaries of the National Association of Automotive Vehicle Manufacturers (ANFAVEA[5]). These procedures generated an initial list that was validated, for innovation efforts, with a survey of patent applications of companies in INPI. In some specific cases, companies were included in the sample for having relevant participation in international agricultural input markets or by indication of specialists in the area, even without a significant record of innovations or relevant participation in the national industry.

After the sample selection, approximately 100 representatives of companies with operations in the country were directly contacted. The operational phase of information collection was made through the application of the structured questionnaire, by electronic mail or in face-to-face interviews of an average duration of 90 minutes. The questionnaire, consisting of eight sections and approximately 40 questions, captured information on human and financial resources for R&D, organization and structure of R&D, the perception of the actors regarding the governmental policy for R&D in Brazil, the major innovations introduced in the country over the past five years, among others.

Inquiries related to human resources demanded detailing of the level of qualification of R&D personnel and the allocation of researchers between research, development, extension, education and consulting activities. In the case of financial resources for R&D, the questionnaire requested the partition of expenditure into five categories: salaries and benefits for R&D personnel, operations of R&D programs, registration fees, official tests, and capital cost for R&D.

The interviews and other activities related to data collection were performed in the first half of 2013 and involved seven researchers in total. The rate of adherence of the companies, measured by the number of questionnaires answered, was about 30%. Although representatives who did not fill out the questionnaire showed interest in participating in the research, criteria related to information confidentiality or the need to contact other areas of the company constituted obstacles to a higher rate of participation.

5 Available in: http://www.anfavea.com.br/anuarios.html

The total private investment disclosed in the study comprises the expenditure of 30 companies in the seed, agricultural biotechnology, agrochemical, machinery and implements sectors. Multisectoral companies had their R&D investments accounted for in their sector with the largest revenue in the country. Such information is contained in the questionnaires. Although the sample represents a small fraction of the universe of companies producing agricultural inputs in Brazil, the research obtained information from leading companies, with a relevant share of the national market.

Table 1 examines the participation of the sample companies in the registration of cultivars and agricultural biotechnologies in Brazil. High participation in maize crops, in which the innovation efforts of the sample resulted in 64% of the total cultivars in the National Register of Cultivars (RNC) and approximately 86% of the total biotechnologies released for commercial use by CTNBio, is a highlight. The participation in the soybean seed market is also worth stressing, with 50% of the biotechnologies and 42% of the new cultivars registered. The soybean and maize seed markets are the largest in the country, with annual sales exceeding US$ 1 billion each. From the point of view of industrial organization, the sample includes information on the six largest companies in the soybean seed market and the five largest in the corn market.

TABLE 1
Participation of the sample companies in the register of cultivars and biotechnologies 1998-2018

Registry of innovation by crop	Soybean			Corn			Cotton		
	Sample	Total	Share	Sample	Total	Share	Sample	Total	Share
Registered cultivars (1998- 2013)	503	1,206	42%	1,529	2,389	64%	40	170	24%
Approved biotechnologies (1998-2018)	8	16	50%	38	44	86%	8	16	50%

Source: RNC, CTNBio, MAPA, Research data.

Regarding the Brazilian agrochemical market, the sample companies accounted for approximately 40% of all new products registered during the 1995-2013 period. From the point of view of share of total sales revenue, the present study collected information from five of the 10 largest companies in the sector, according to the ranking presented in BNDES (2014). Data obtained from ANFAVEA indicate that the sample companies were responsible for approximately 70% of the harvesters and 40% of the wheeled tractors produced in the country between 1995 and 2012.

The results of the work are representative of the total private investment in agricultural R&D in the country. All aggregate values on market size (revenue and production) were obtained from associations of input industries. Since only one company in the sample is listed in the Brazilian stock market, we could not use accounting reports as an information source. It is important to emphasize that there is a relevant number of publicly traded agricultural input companies with shares negotiated in the market in China and India, mainly companies controlled by local economic groups, a fact that expands the disclosure of accounting reports and facilitates access to information about R&D investments.

4. Recent evolution of investments in agricultural research in Brazil

Brazil's wider participation in the international trade of agricultural products and the strengthening of intellectual property rights, as a result of the Innovation Law (Law n. 10,973/2004), the Law on the Protection of Cultivars (Law n. 9,456/1997) and the Law of Industrial Property (Law n. 9,279/1996), have rendered the Brazilian agricultural input markets some of the most attractive and rapidly growing in the world. Indeed, these elements were decisive for recent changes in agricultural research investments in the country.

Table 2 compares the results of the present study and private investments in agricultural R&D in Brazil in the mid-1990s, as exhibited in Roseboom (1999). Regarding public investments, Table 2 reproduces the data disclosed in ASTI (2019). The comparison allows the conclusion that public investments persist with the largest share of the total agricultural R&D in the country, although they have reduced their participation by 10%, from 94% in 1995 to 84% in 2012. The reason behind this change was the increase in private investments, which reached, in 2012, a value about five times higher than that recorded in 1995. Along the same period, the compound annual growth rate (CAGR) of private R&D reached 11%, while the CAGR of public R&D was 4%.

According to the primary data obtained by the present study, private companies invested a total of US$ 394 million (R$ 770 million converted into 2012 dollars) in agricultural R&D activities in Brazil in 2012. The value was divided between expenses in the sectors of seeds and agricultural biotechnologies (R$ 547 million), agricultural machinery and implements (R$ 131 million) and agrochemicals (R$ 92 million). The total number of full-time employees (FTE) who worked as researchers in the private sector that year was 1,955, divided between seed and agricultural biotechnology (1,475 researchers), agricultural machinery and implements (392 researchers) and agrochemical (88 researchers) companies. Spending on salaries for R&D personnel and on costs related to testing and new product registrations concentrated more than 80% of private investments. The workforce with a postgraduate degree represented less than 20% of the R&D personnel in the private sector.

TABLE 2
Recent evolution of investments in agricultural research
Brazil – 1995-2012

Agricultural research (2012 US$ million)	1995	2012
Private investment	75	394
Public investment	1,114	2,108
Private + public (total)	1,189	2,502
Private share (%)	6.0	16.0
Public share (%)	94.0	84.0

Source: Roseboom (1999), ASTI (2019), Research data.

Based on the information collected, it can be argued that the agricultural input firms concentrated their investments in activities of adaptation, registration and commercial release of products developed in laboratories located at the headquarters of transnational companies. In this sense, Prado *et al.* (2014) estimate that expenditures in the final stages of the development process of a genetically modified plant, corresponding to field testing activities, data generation and analysis, drafting of documents and submission to regulation, are approximately US$ 60 million. Beyond the registration fees for new products and wages, this amount is allocated to the maintenance of infrastructure for R&D activities, such as experimental farms and test and analysis laboratories. It is worth stressing that, in the case of agrochemicals, even for less R&D-intensive formulated products, representatives of companies opposed the high value of fees charged for the registration of innovations in the country.

In another perspective, the results indicate that national companies had a low relative participation in Brazilian R&D efforts. Transnational corporations accounted for 79% of the private agricultural R&D in 2012 and employed the vast majority of researchers with postgraduate degrees. National capital companies carried out about 21% of the total private R&D and employed approximately 20% of researchers with postgraduate studies. The reduced participation of Brazilian private capital was arguably influenced by the large number of acquisitions of national companies recorded in the last decades, mainly in the sectors of seeds, biotechnologies and agrochemicals.

Profit reserves were the main source of funds for private investment in agricultural R&D in Brazil. However, the period recorded the strengthening of institutional arrangements such as tax exemptions, tax refunds, subsidized credits and partnerships with public research organizations as mechanisms employed by the government to indirectly finance private R&D spending. About 80% of the companies participating in research got a hold of tax credits granted by the Law of Good (n. 11,196/2005) at least once between 2006 and 2014. According to Araújo, Rauen and Zucoloto (2016), the companies benefiting from the Law of Good invested up to 11% more in R&D than the amount they would have invested had there been no tax incentive. To Fuglie (2016), the liberal policies practiced in recent decades by the Brazilian government have achieved positive results in attracting foreign investments for innovation activities in the agricultural input industries.

The magnitude of foreign investments in Brazil differs from the recent dynamics observed in India (PRAY; NAGAJARAN, 2014) and China (HU *et al.*, 2011). In these countries, national companies have consolidated prominent positions in agricultural R&D activities and in the hiring of researchers with postgraduate degrees. Pray and Nagajaran (2014) indicate that private investments accounted for approximately 25% of the total and that Indian companies were responsible for 62% of that amount in 2009. According to the authors, Indian seed, agrochemical and agricultural machinery companies compete with foreign businesses in the domestic market and successfully expand their operations to foreign markets.

In the Chinese case, state-owned enterprises play an important role in developing new inputs, mainly because the Chinese government imposes restrictions on foreign investment in agricultural R&D, which can only be carried out in the country through partnerships with Chinese state-owned organizations. Pray and Fuglie (2015) point out that, despite the low levels of R&D spending by foreign or non-state domestic firms, Chinese companies have used direct acquisitions from foreign enterprises to internalize technologies and knowledge.

In another perspective, Table 3 presents the estimates of technological intensity of the agricultural input sectors in Brazil in 2012, obtained from the division between the total private investments in R&D and the total sales revenue for the respective sectors. The companies were grouped into 3 categories, according to the magnitude of sales revenues in the country in 2012. Large companies correspond to those with revenues exceeding R$ 1 billion and average companies to revenues below this value.

In the agrochemical sector of Table 3, the category "other manufacturers" concerns the company supplying products for biological control. It is noteworthy that large and medium-sized companies in this sector also have products for biological control in their portfolio, but the largest share of their revenues comes from the commercialization of agrochemicals. In the seed and biotechnology sector of the same table, the regional company category represents a seed multiplier that licenses genetic material and does not develop cultivars, but has an R&D sector with investments in field tests, registration and regulation of new products. In the agricultural machinery sector, in turn, the category "other manufacturers" represents a company offering software for precision farming.

De Negri and Cavalcante (2013) estimated, based on the data by 2011 PINTEC, that the R&D intensity in the high technology sectors of the Brazilian manufacturing industry was 2.28%, and 1.27% in the medium-high technology sectors. The evaluation of agricultural input companies, as shown in Table 3, attests to the high technological intensity of the sector of seeds and agricultural biotechnologies, which invested the equivalent of 10.42% of the sales revenue in R&D in 2012. Thus, the seed and biotechnology sector can be inserted in the high technological intensity category of the national industry. In turn, the R&D intensity of agricultural machinery companies presented values corresponding to the class of medium-high technological intensity of the national industry, as estimated by De Negri and Cavalcante (2013).

Regarding the organization of R&D activities, all sample companies reported participation in consortia, partnerships, collaboration agreements and other forms of collective actions for technological progress, as a way to share the sunk costs and the risks of the initial stages of the innovation process. The most adopted model of these actions, as described in the questionnaire, involved agreements between companies and public organizations. In other less frequent cases, companies were contracted for the provision of technological services to other companies. Collaboration between rivals makes sense when we consider the initial stage, the uncertainty and the regional character of biotechnological trajectories and precision farming. From the point of view of innovation strategies, contracting technological services can be a mechanism for accessing competencies which are external to the firm.

TABLE 3
Research sample and sectoral R&D intensity
Brazil – 2012

Sector	Sales value in 2012 (R$ million)	Research sample (n. of firms)	Intensity of R&D spending in the sector (%)
Agrochemicals	9,700		0.95
Large companies (>R$ 1 billion in sales)		3	
Medium-sized companies (<R$ 1 billion in sales)		3	
Other manufacturers		1	
Seeds and biotechnologies	5,200		10.42
Large companies		3	
Medium-sized companies		4	
Regional companies		1	
Agricultural biotechnology companies		10	
Agricultural machinery	10,300		1.27
Large companies		2	
Medium-sized companies		2	
Other manufacturers		1	

Source: Research data.

Along the period analyzed, public organizations maintained a relevant position in the Brazilian agricultural research, especially in the role of suppliers of information and technological services which are necessary to adapt innovations to the tropical conditions of Brazil. The efforts in this direction were decisive in attracting investments from large transnational corporations of the agricultural input sectors. In some cases, large corporations made direct investments in the country, acquiring or constructing research facilities and signaling a lasting commitment to the national economy.

Without a doubt, these actions have strengthened the development and gains in agricultural productivity recorded in the recent period. However, such dynamics should also be discussed in the light of the direct contributions of these companies to the Brazilian GDP, without losing sight of the incessant capitalist dispute for the economic surplus resulting from the diffusion of innovations, which potentially creates conflict between groups of consumers, farmers and enterprises.

5. Analysis of sectoral technical progress

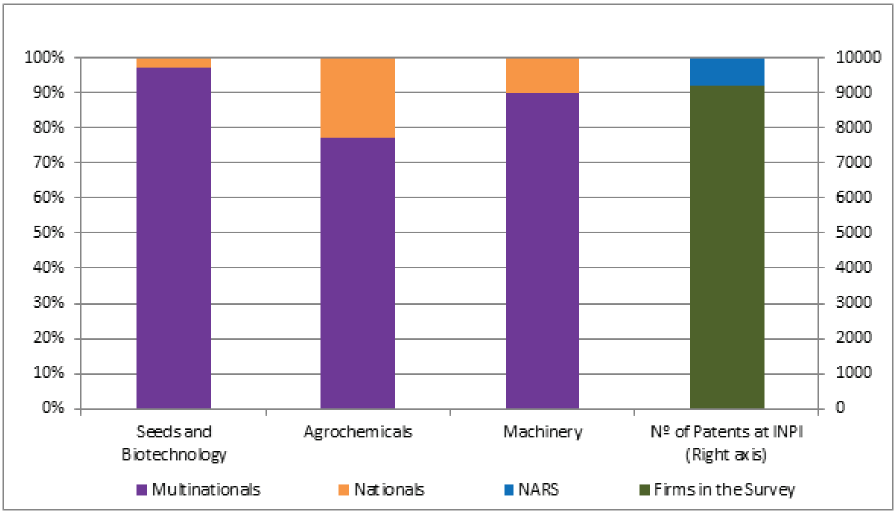
The patenting activity is often taken as an indicator of the result of R&D efforts and of the technological progress in companies, industries or sectors of the economy. This is because patent licensing is the most measurable flow of technologies from innovative efforts. Hence, in order to analyze the technological progress of the sample companies, data on the filing of patents from the group of companies that participated in the research were compiled from INPI and the Web of Knowledge/ Derwent Innovations Index.

As shown in Figure 2, the sample companies filed approximately 9,500 patents in INPI between 1995 and 2012. It can also be seen that the national companies had a participation of less than 10% in the application of patents in the seed and agricultural biotechnology sectors, approximately 25% in the agrochemical sector and about 10% in the agricultural machinery and implements sectors. Note that part of the patents of the sample companies had previously been filed in other countries, which indicates a high weight of development activities (D) in investments in the country and dependence on research (R) developed in other countries.

Figure 2 also draws a comparison between the patenting activity of public agricultural research organizations, components of the National Agricultural Research System (SNPA), and applications made by the group of sample companies. In this regard, the small number of patents filed in INPI by the members of the SNPA-Embrapa and state agricultural research organizations can be observed. In contrast, when comparing the records of scientific papers published in journals indexed to the Scopus database, there is a reversal of positions, with the SNPA organizations having the largest number of publications to the detriment of researchers affiliated to private companies active in the country.

It is important to emphasize that, in most cases, R&D investments in public agricultural research organizations are concentrated in low-appropriability areas of knowledge and technologies, which produce results with characteristics of public goods. However, weak patenting activity constitutes a bottleneck to the financial self-sufficiency of SNPA organizations. From a strategic standpoint, a strong reliance on National Treasury resources can generate discontinuities in R&D programs in public organizations, especially long-term programs. Great uncertainty about project continuity has the potential to drive away long-term private investments, such as the construction of research facilities and laboratories in the country.

FIGURE 2
Patenting activity
Brazil – 1995/2012



Source: INPI, Research data.

In order to include more variables in the evaluation of technological progress, all the patents of the sample companies in the International Scientific Indexing (ISI) – Web of Knowledge/Derwent Innovations Index were extracted. The search was oriented so as to return the records that had at least one of the sample companies as an applicant. The companies were grouped into three sectors – seeds and biotechnologies, agricultural machinery, and agrochemicals – according to the magnitude of R&D efforts. That is, companies with activities both in agrochemicals and in seeds and biotechnologies were accommodated in the sector that corresponded to the largest portion of their R&D investments in Brazil in 2012, as reported in the questionnaire. To restrict the search result to the patents filed in the country, the truncation operator "BR*" was employed in the patent number field.

The information obtained from the ISI database was treated to identify the technological areas that gained or lost relevance among the patents filed in Brazil from 1995 to 2012. To do so, the relative frequency indicator, the relative frequency variation and the growth rate of the technological subclasses were measured according to categories of the International Patent Classification (IPC)[6] of the World Intellectual Property Organization (WIPO).

6 Information on the subdivision of IPC technology areas is available in ipc.inpi.gov.br/

The relative frequency indicator, adapted from Fornari *et al.* (2015), corresponds to the ratio between the number of records of the technological subclass and the total of patents filed in the period, expressed as follows:

$$\text{Relative Frequency of the Subclass } (i)\ (\%) = \frac{\text{Number of applications in the Subclass (i)}}{\text{Total number of patents in the sample}} \quad (1)$$

with the variation of the relative frequency of the subclasses being effectively evaluated in the study, and measured as follows:

$$\Delta\ \text{Frequency of the Subclass } (i)(\%) = Freq.(i)_{2012:1995} - Freq.(i)_{1994:1970} \quad (2)$$

The temporal division in the expression (2) aims to compare the total number of patents filed in two different periods: from the foundation of INPI (1970-1994) to the phase evaluated by the research (1995-2012).

The growth of subclasses was evaluated by calculating the percentage rate of growth, following this formula:

$$\text{Growth rate of the Subclass (i)} = \frac{\text{No. of applications (i)}_t - \text{No. of applications (i)}_{t-1}}{\text{No. of applications (i)}_{t-1}} \quad (3)$$

Figures 3, 4 and 5 present the trajectory of the technological subclasses in the sectors of seeds and biotechnologies, agricultural machinery, and agrochemicals, respectively. In order to increase the power of analysis of the results, we decided to restrict the data of the graphs to the subclasses present in at least 10% of the total patents in each sectoral sample. At the end of the text, annex presents the IPCs and describes the declining and emerging technological subclasses in the agricultural input industries. The position of the points in the graphs makes it possible to visually identify the technological subclasses that lost or gained relevance in patenting from 1995 to 2012.

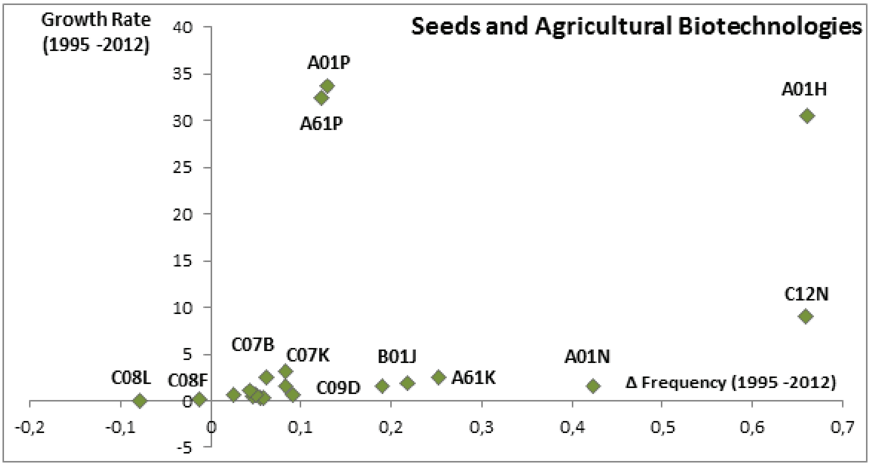
The horizontal axes of the graphs translate the variation in the frequency with which a given technological subclass is cited in the total patents filed. The farther right a subclass is positioned, the greater relative importance it gained in the patent pool in the 1995-2012 period. For instance, in Figure 3, subclass C12N[7] recorded a variation of approximately 0.7 in the relative frequency indicator. This means that this subclass had an increase, between 1995 and 2012, of approximately 70% in

7 The Annex presents and describes the declining and emerging technological subclasses, highlighted in the graphs in Figures 3, 4 and 5.

its participation as a base of knowledge used in the technological progress of the companies of the sectoral sample. On the other hand, still in relation to Figure 3, subclasses C08L and C08F lost relevance in innovation efforts and presented a negative relative frequency variation.

The vertical axes of the graphs express the percentage growth rate of the technological subclasses between the amount recorded up to 1994 and that observed in the 1995-2012 period. Points near the upper limit of the vertical axis indicate that the subclass recorded growth in patent applications when compared to the other subclasses. For example, Figure 3 indicates that subclasses A01P, A61P and A01H had a total number of patent applications from 1995 to 2012 that was approximately 35 times higher than that observed up to 1994. Similarly, still in Figure 3, subclasses C08F and C08L practically did not increase their total number of applications from one period to the next.

FIGURE 3
Dynamics of the technological areas in the sectors of seeds and agricultural biotechnologies
Brazil – 1995/2012



Source: Derwent Innovations Index, Research data.

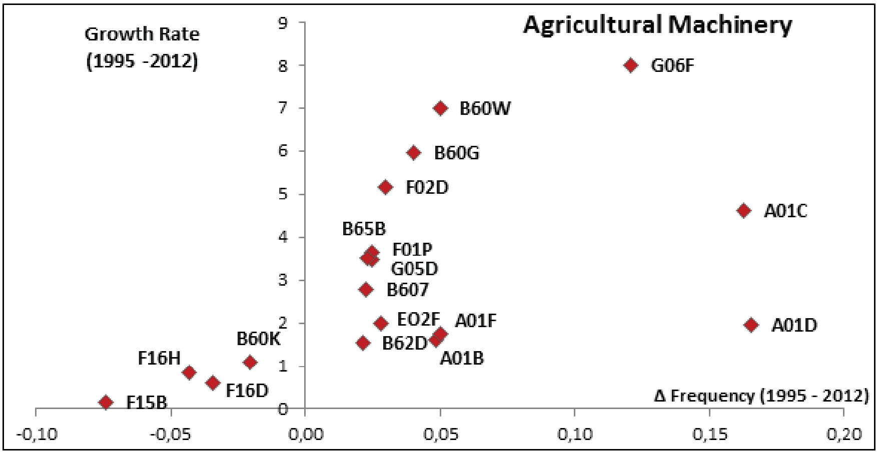
From the results obtained, it can be seen in Figure 3 that subclasses A01P, A61P, A01H and C12N have achieved a prominent position in the recent technological dynamics of the seed and agricultural biotechnology sectors. These subclasses comprise biotechnology-based knowledge, applied to technologies in the fields of genetic engineering and mutations; composition, maintenance, conservation and propagation of microorganisms; new plants and processes to obtain them; reproduction of plants by means of tissue culture techniques; plant growth regulators; and biocidal, pest repellant or pest attractant. In contrast, declining subclasses C07C, C07D, C08F and C08L cover chemistry-based knowledge, incorporated into technologies applied to the composition and preparation of macromolecular compounds.

The analysis of emerging and declining technological subclasses indicates the structural transformation of private R&D activities, materialized in the substitution of investments in chemical products by biological products. As a result, there is an increase in investments in technologies for genetic improvement and engineering, production of biological control agents, inoculants and traits. Patents filed by Brazilian companies in the seed and biotechnology sectors indicate a specialization in knowledge applied in technologies for the development of microorganisms of agricultural interest and enzymes for the industry of biofuels. Another relevant fact relates to the intensification of patenting in the sample companies, which, between 1995 and 2012, filed a total number of patents that was 30% higher than that recorded up to 1994.

With regard to the increase in the number of patent applications, the companies of agricultural machinery in the sample doubled their total of patents in Brazil between 1995 and 2012. The acceleration of patenting resulted from the emergence of technological areas poorly exploited by companies until then, as shown in Figure 4. In particular, subclasses G06F and B60W comprise technologies applied to the electrical processing of digital data and in control systems for vehicles and sub-units, respectively. The results of the analysis are consistent with the greater demand for technologies for precision farming and the automation of tractors and agricultural machinery. Therefore, market pressures explain investments in knowledge bases related to information technologies, communication and data mining.

In Figure 4, we can see that subclasses F16H, F15B, F16D and B60K have lost relevance in the sample of agricultural machinery companies. These declining subclasses are related to the knowledge base in mechanical engineering, applied to the development of components such as gearing systems, couplings for transmitting rotation, arrangement or mounting of propulsion units or of transmissions in vehicles. The loss of relevance of these technological trajectories is arguably the product of the strengthening of supplier companies, which, with the accumulation of knowledge and learning, have assumed a prominent position in the technological progress of the production of tractor components.

FIGURE 4
Dynamics of technological areas in agricultural machinery sectors
Brazil – 1995/2012



Source: Derwent Innovations Index, Research data.

Brazilian firms have also benefited from the innovations developed by component suppliers and, therefore, achieved competitive advantages in market niches. The patents from the Brazilian sample companies were concentrated on technologies used in specific tasks of the agricultural production: soil tillage, planting, sowing, fertilization, spraying and harvesting. It is worth stressing that products of this type constitute markets with significant volume and value of sales, especially in crops with large planted areas in the country, such as sugarcane, corn, coffee and soybean.

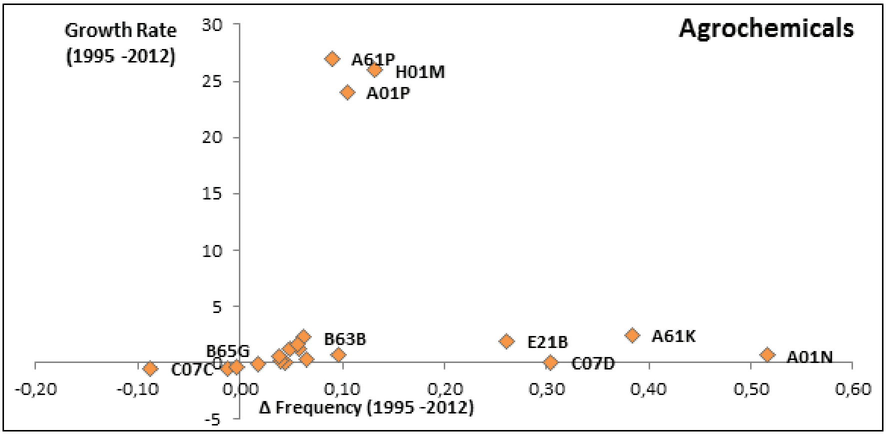
The agrochemical sector recorded the lowest growth rate in the number of patent applications in the country, when compared to the other sectors of the sample. The reduction in R&D efforts in pesticides is a global movement, driven by the reorientation of investments in research by the leading companies in the agricultural input sectors. This fact is attributed to the depletion of the technological trajectory of agrochemicals, caused by increasing costs of discovery of new molecules and a strengthening of positions contrary to pesticides in the public opinion.[8]

In fact, the results presented in Figure 5 allow us to observe that the recent technological dynamics of the agrochemical sector in Brazil does not differ from the global trajectory. Emerging subclasses A61P and A01P relate to biotechnology-

8 On this issue, we highlight the report of The Economist, which brings information about the change of perception of companies and the public opinion about technological trajectories in agriculture based on chemical knowledge: https://www.economist.com/business/2018/11/17/upheaval-in-the-chemicals-industry

based knowledge and C07C includes chemistry-based knowledge incorporated in technologies applied to the composition and preparation of macromolecular compounds. However, it is noteworthy that even with the weakening of the patenting activity and the lower participation of this sector in agricultural R&D investments, there was an increase in the registration of new agrochemical products in Brazil in the period under scrutiny. This fact is due to the commercial release of formulated and equivalent products previously marketed in other countries. Biological products for crop protection accounted for about 10% of all products registered in the same period covered by Figure 5, with special focus on the participation of national companies, with about 90% of the innovations recorded.

FIGURE 5
Dynamics of technological areas in the agrochemical sector
Brazil – 1995/2012



Source: Derwent Innovations Index, Research data.

Broadly, Pray and Fuglie (2015) state that the seed, biotechnology and agricultural machinery industries were the main responsible for increasing private investments in agricultural R&D in recent decades. The sectoral dynamics of patent applications in Brazil reinforces the conclusions obtained by the authors and also highlights the growth of private investments in research for the production of biofuels. As regards the patenting activity of the national sample companies, the results of the analyses indicate the specialization in stages of agricultural production – as in the case of the machinery sectors – or in agricultural crops – as in the case of the seed and biotechnology sectors.

6. Conclusion

This study examined the dynamics of Brazilian private agricultural research in a circumscribed period, 1995 -2012, and interpreted the results obtained in the light of the international literature. We sought to contribute to studies in the field of the economics of agricultural research through a survey and dissemination of primary data from private investments in agricultural R&D carried out in Brazil. The interpretations and stylized facts along the text interacted with previous studies which evaluated the dynamics of private investments in the 1990s. We expect to have continued this research line and to have built reference bases for subsequent studies.

As previously discussed, between 1995 and 2012, there were structural changes in the Brazilian agricultural input industries, with significant outcomes on technological progress and R&D investments. During the period under scrutiny, the Brazilian authorities regulated the protection of intellectual property of agricultural cultivars and biotechnologies, there was a strong expansion of the Brazilian participation in international trade and an increase in public investments in research, especially at Embrapa. Jointly, these factors rendered the Brazilian agricultural input markets attractive, and they started to have segments with revenues of billions of dollars per harvest.

It can be concluded that private investments in Brazil were allocated in the final stages of the innovation process. Investments in activities that are highly knowledge-intensive and have greater demand for skilled labor were made mostly in developed countries, in the headquarters and laboratories of the global leading transnational companies of the agricultural input markets. The growing number of new products registered in the country justifies the significant increase in private investments and the high R&D intensity of the target sectors of this study. Nevertheless, the research highlighted the small relative participation of Brazilian companies in the total private investments and in the registration of new products.

The analysis of the patenting activity indicated that national agricultural input companies adopted innovation strategies focused on crops or stages of production that are not considered by the R&D programs of large transnational corporations. The same idea applies to sectors in which regional specificity is decisive to successfully adapt technologies, as is the case of information and communication technologies. Largely, over the period covered by the study, small innovative national companies became attractive targets of acquisitions and were hardly able to resist the proposals of large transnational corporations.

As a conclusion, it is important to emphasize that there is an ongoing strengthening of new technologies and strategies for agricultural research, with elements that are susceptible to evaluation. In this new model, large enterprises have intensified the search for knowledge and technologies which are exogenous to their R&D structure, allocating larger portions of investments in hiring research services or even in start-up accelerators. From the point of view of technological dynamics, the expiration of the protection period of patents related to transgenics and the commercial release of products developed using precision genetic engineering and new improvement technologies point to a new cycle of structural transformations in private investments in agricultural R&D (DIAS; SILVA; CARNEIRO, 2017). It is therefore important to evaluate their main characteristics and impacts in subsequent studies.

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ANNEX

Declining and emerging technological subclasses.

Technological subclass	Description – IPC/WIPO
A01H	New plants or processes for obtaining them; plant reproduction by tissue culture techniques
A01P	Biocidal, pest repellant, pest attractant or plant growth regulatory activity of chemical compounds or preparations
A61P	Specific therapeutic activity of chemical compounds or medicinal preparations
B60K	Arrangement or mounting of propulsion units or of transmissions in vehicles; arrangement or mounting of plural diverse prime-movers in vehicles; auxiliary drives for vehicles; instrumentation or dashboards for vehicles; arrangements in connection with cooling, air intake, gas exhaust or fuel supply of propulsion units in vehicles
B60W	Conjoint control of vehicle sub-units of different type or different function; control systems specially adapted for hybrid vehicles; road vehicle drive control systems for purposes not related to the control of a particular sub-unit
C07C	Acyclic or carbocyclic compounds
C07D	Heterocyclic compounds
C08F	Macromolecular compounds obtained by reactions only involving carbon-to-carbon unsaturated bonds (production of liquid hydrocarbon mixtures from lower carbon number hydrocarbons, e.g. By oligomerisation)
C08L	Compositions of macromolecular compounds
C12N	Microorganisms or enzymes; compositions thereof (biocides, pest repellants or attractants, or plant growth regulators containing microorganisms, viruses, microbial fungi, enzymes, fermentates, or substances produced by, or extracted from, microorganisms or animal material; medicinal preparations; fertilisers); propagating, preserving, or maintaining microorganisms; mutation or genetic engineering; culture media (microbiological testing media)
F15B	Systems acting by means of fluids in general; fluid-pressure actuators, e.g. servomotors; details of fluid-pressure systems, not otherwise provided for (engines, turbines, compressors, fans, pumps; fluid dynamics; fluid clutches or brakes; fluid spring dampers; fluid gearing; pistons, cylinders, gaskets; valves, taps, tap handles, tank floats; safety valves with auxiliary fluid operation of the main valve; fluid relief valves; pipes, pipe joints; lubrication)
F16D	Couplings for transmitting rotation (gearing for conveying rotation, e.g. fluid gearing); clutches (dynamo-electric clutches; clutches using electrostatic attraction); brakes (electrodynamic brake systems for vehicles in general; dynamo-electric brakes)
F16H	Gearing
G06F	Electric digital data processing

Source: INPI (2018)