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The Brazilian sugarcane innovation system

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ABSTRACT

Ethanol has recently been of great interest worldwide because it is a viable economic alternative to petroleum products and it is a renewable source of energy that mitigates the emission of greenhouse gases. Brazilian bioethanol from sugarcane is the most successful case at the world level because of its low cost and low level of greenhouse gas emissions. Brazil's success with sugarcane cannot be understood as based solely on a natural comparative advantage, but as a result of efforts that culminated in a positive trajectory of technological learning, relying mostly on incremental innovations. The purpose of this article is to analyze the key aspects of the innovation system built around the Brazilian sugarcane industry. It is based on the national innovation systems approach according to which innovation results from the interaction of different institutional actors. Institutional arrangements are analyzed as the basis for the innovative process, in particular R&D and the innovation policies and strategies of the main players in the sugarcane sector, including sugar and ethanol mills, industrial goods suppliers, public and private research institutions, and governmental agencies.

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1. Introduction

Ethanol produced from biomass has recently drawn attention worldwide for two main reasons. First, it is a viable alternative to light vehicle fossil fuels, which have risen in price significantly in recent years. Second, ethanol is a renewable energy source and as such mitigates the effect of greenhouse gas emissions.

Although Brazil ranks second in ethanol production after the United States (Licht, 2007), it has developed ethanol production from biomass more than any other country worldwide. Unlike the US system, which uses corn as its raw material, the Brazilian system produces ethanol from sugarcane, the traditional raw material for sugar production. The Brazilian route is more competitive and generates less greenhouse gases than the US route, mainly because the energy required to run the mill comes from biomass in the form of sugarcane bagasse.

The purpose of this article is to analyze the main characteristics of the Brazilian innovation system structured around the sugarcane agroindustry. Brazil's success with sugarcane cannot be understood solely as deriving from a natural comparative advantage. Above all, it is the result of a virtuous trajectory of technological learning strongly based on incremental innovations. The turning-point in this process was the National Alcohol Program (Proalcool), launched in 1975 after the first oil shock. This program enabled Brazilian agroindustry to embark on a virtuous trajectory of innovation–diffusion, steadily raising productivity and lowering production costs in both the agricultural and industrial stages. The technological progress benefited the production of both fuel alcohol and sugar, of which Brazil became the world's leading producer.

This study is based on the national innovation systems approach (Lundvall, 1992; Freeman, 1987; Nelson, 1993). According to this approach, the innovative performance of a country, region or even a given sector cannot be captured by focusing on the efforts and achievements of companies individually. On the contrary, innovation is a process that results from the interaction of players of the same or different institutional natures. Thus, the institutional arrangements underpinning the innovative process were analyzed, in particular research and development (R&D) and the innovation policies and strategies of the main players in the sugarcane sector (sugar and ethanol plants, capital goods suppliers, public and private research institutions, and government agencies).

This paper is a side result of a study undertaken by a research group from the University of Campinas to explore the futures scenarios for the Brazilian ethanol industry (CGEE, 2009). In one of the chapters of this study (Chapter 10) the authors describe the research institutions and the funding mechanism of the Brazilian sectoral innovation system. The sources of information used in this paper are public data, and direct contact with important specialist of the sugarcane industry that were conducting or participating to this study.

The paper is divided into six parts in addition to this introduction. The second section reviews the literature on

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national and sectoral innovation systems. This is followed by a description of the historical background in which the Brazilian sugarcane agroindustry emerged. Section 4 depicts the efforts, strategies and performances of the key actors in this sectoral innovation system. Section 5 discusses the interactive dynamism of the system's main components. The conclusions present some remarks on the potential of Brazil's ethanol innovation system and some of the challenges it faces.

2. Sectoral innovation systems

Innovation was first introduced in the economic literature by Schumpeter (1934), who argued that innovation was the main cause of economic development, and also of disequilibrium in the economic system. Innovations were disruptive and caused a discontinuity in the economic status quo. Schumpeter credited entrepreneurs with the main responsibility for innovations, which enabled them to perform new productive combinations, but he also acknowledged that employees, managers and directors were able to execute new entrepreneurial functions. He later extended this view by pointing out that large corporations were able to manage innovation on a larger scale in industrial laboratories (Schumpeter, 1942).

Schumpeter clearly separated innovation from invention in his early writings, distinguishing emphatically between the creativity of inventors and the economic leadership of the innovative entrepreneur. Inventors do not usually have the capacity to create new markets, while many innovations do not require inventions. The meaning of innovation for Schumpeter was broad, including other forms besides technological innovation. In this respect, he saw scientific and technological activities as having a different rationale than innovation. In his later writings, Schumpeter recognized that large firms could organize systematic scientific and technological research with the aim of innovating.

However, Schumpeter acknowledged that innovation was not only driven by individual firms. Many investors and financiers promoted innovation by assuming the risk of creating new monetary resources to finance innovation. This view nevertheless restricted innovation to the business sector.

The role of scientific and technological research conducted outside the firm for the purpose of innovation is highlighted in the literature on science policy by such authors as Bernal (1939) and Vannevar Bush (1945), both closely related to the scientific community. They set out to demonstrate the importance of basic science for economic and social progress. However, they recognized, as did Schumpeter, that scientific research had an internal rationale that was quite different from the firm's economic search for profit.

The concept of a national innovation system aims to integrate several kinds of organization with very different institutional rationalities in the innovation process. The relationships among these actors explain the interactive nature of innovation. This concept was first introduced by Freeman (1987) in analyzing the Japanese catching-up experience and demonstrating the role of national institutions in this success story. His approach was an attempt to explain innovation at the level of the economic system, demonstrating that innovation by firms could not be explained without comprehension of the social, political and institutional issues that manifested themselves preferentially at the national level. Thus innovation was not an isolated initiative by one firm, but resulted from the interaction of many actors.

Lundvall (1988) was working in the same direction but was concerned with the interactions among firms, mostly users and suppliers. Firms were not isolated and needed a large amount of knowledge from other firms. Both users and producers of capital goods had to interact very closely to produce effective new technologies. These interactions occurred more frequently inside national borders, making cultural factors critical to any attempt to explain them.

If interactions among firms are more understandable because they happen inside the same productive and innovative logical framework, even if they could come into conflict because of competitive pressures, interaction between firms and research-oriented institutions had to be explained by a different conceptual framework. The linear model with its separation of the logic of public science and the rationale of the private firm was long used to explain interactions between research and industry interactions. However, the chain-linked model introduced by Kline and Rosenberg (1986) served to demonstrate that scientific research was not prior to or independent from firms' efforts to innovate.

Innovation systems comprise not only firms and R&D organizations, but also government agencies, education and training organizations, credit organizations, industrial and science and technology policies, institutions and rules, etc. All these elements are concerned with the generation and diffusion of knowledge for innovation inside a national economic system (Freeman, 1987; Lundvall, 1992; Nelson, 1993).

Evolutionary literature was decisive to demonstrate that firms and research institutions were related to technological regimes. Freeman (1982) demonstrated that firms specialize in specific technological bases and innovate in different ways according to their core business. This later enabled Dosi (1984) to create the concept of technological trajectories to explain technological evolution and firms' innovative strategies. At the same time, Pavitt (1984) created a taxonomy of industries based on the main basic features of their technological regimes. Some specificities, such as industrial organization, technological opportunities and appropriability, help to explain how firms interact in the innovation process. However, other kinds of player, such as research organizations, also specialize in specific scientific and technological fields. The nature of these research organizations and their interaction with firms also helps to understand sectoral technological regimes.

The application of sectoral innovation systems analysis to energy is very instructive. The competition between energy sources is essentially a competition between technologies. Thus much of the energy questions are about the competition of different technology systems. The possibilities for new energy sources to become competitive with the well established fossil fuels technologies is a matter of concern because of the long lasting substitution delays. New energy technologies go against well perceived interest of the established technologies. The market failures for these emerging technologies are "poorly articulated demand, economies of scale and experience and other sources of increasing returns, local search processes among the firms and market control by incumbents." (Jacobsson and Johnson, 2000, p. 631). Therefore, the constitution of alternative energy technological systems requires strong attention on new institutions, like regulatory framework or the education system, new markets for these new energy sources, new firms, networks functioning appropriately, adequate legitimacy among the public opinion, are all important aspects allowing the diffusion of new technological system (Jacobsson and Bergek, 2004).

In the sugarcane industry, the organization of the productive process and the technological trajectory were determinant to explain the competitive success and also the survival of this industry during the low oil price period. As in many other agroindustries, the food industry dominates agriculture in the generation of new technologies. However, innovation in the agricultural phase is decisive for the technological regime.

Product innovations play a very limited role compared to process innovations. This can explain why most of the research is conducted on a cooperative basis. Research is frequently taken up by public (government-funded) institutions owing to lack of appropriability of the innovation returns.

Another aspect of the technological nature of the Brazilian sugarcane industry that it is important to understand relates to the nature of the innovation process in developing countries. Since the early work of Katz (1984), Teitel (1984), Kim (1980), Lall (1982), and Bell et al. (1984), there has been increasing concern about endogenous innovation generation in developing countries, and about how technological efforts and capabilities can contribute to the catching-up process. While recognizing that international technology transfer is the main source of technological progress in the initial stages of industrial development, these authors explained that the effective absorption of technology requires local efforts, because knowledge is not completely available and has a dominant tacit component, and also because technology needs significant adaptation efforts to operate effectively. They also pointed out that less developed countries have important technological activities that engender predominantly incremental innovations. Based on these learning processes, some developing countries became exporters of technology in the 1970s (Dahlman and Sercovich, 1984).

There is a dearth of studies about national and sectoral innovation systems in developing countries. An important effort was organized under Nelson (1993). Several national studies about Brazil, Argentina, Korea, and Taiwan were conducted, revealing important features of these systems. With regard to national systems in Latin America, important work was undertaken by Arocena and Sutz (2000), who exposed some important features of these systems, such as weak interactions among actors and lack of coherence between technological and economic policies. These features had previously been analyzed by Herrera (1972), Sabato and Botana (1970), and Fajnzylber (1983).

More recently, the volume and variety of research on regional and sectoral systems of innovation in developing countries has increased. These studies focus on high-tech as well as low-tech industries. The success of sectoral systems of innovation has been far greater in Asian countries than in other regions of the developing world (Hobday, 2000; Oyelaran-Oyeyinka and Rasiah, 2009). However, in Latin American countries sectoral systems are more effective in low-tech industries, such as agriculture and the food industry (Marin Carbajal and Padilla Hernándes, 2008; Orozco and Diaz, 2008).

Even if there is an increasing concern about technology systems in the energy sector, we can find some few studies applied to renewable energies (Foxxon et al., 2008) and to biomass innovation systems (Negro et al., 2007). There still a lack of sectoral innovation approach applied to Brazilian sugarcane ethanol. Several studies about Brazilian ethanol industry recognize great importance of technological progress in its productive success (Moreira and Goldemberg, 1999; Hira and Oliveira, 2009). However, there is a lack of studies that depict the institutional arrangement which lies behind the innovation dynamics of the sugarcane agroindustry, and its evolution since the Proalcohol program.

3. Origins of the Brazilian sugarcane sectoral innovation system

Sugarcane was the first commercial crop of the Portuguese colony. During the 16th and 17th centuries, the Northeast region of Brazil became the foremost producer and a world exporter of raw sugar based on the plantation economy and on slave labor brought from Africa. Although this was a prosperous economy, the linkages for the region were always limited. In the middle of the 17th Century the Dutch left the Brazilian Northeast, taking sugarcane to the Caribbean. As a result, the Brazilian sugar economy receded. New sugar plantation economies rapidly emerged in the British, Spanish, and French colonies in the Caribbean, competing with the Brazilian Northeast and displacing its hegemony as a sugar producer. As a result, the Northeast region entered a process of stagnation that was to last centuries (Furtado, 2001).

The Brazilian sugar production system remained in the doldrums for a long period, beginning to change, albeit with low productive dynamism, only after the 1929 crisis, when a new federal government that emerged from the Revolution of 1930 helped the weak economy of the sugar agroindustry by allocating resources to buy sugar for buffer stocks and creating the IAA (Sugar and Alcohol Institute) in 1933. Growth of the domestic market due to industrialization turned out to provide a natural replacement for external demand. The same period saw the introduction of ethanol blended with gasoline as automotive fuel. Difficulties with the transportation of sugar produced along the coast of the Northeast region intensified during world war two and contributed to consolidation of the sugar industry in São Paulo, located in the Southeast region. The industry here became more dynamic thanks to the use of modern production techniques and proximity to an industrial complex which produces capital goods, as well as significant research institutions, such as the IAC (Campinas Institute of Agronomy) and Esalq (the Luiz de Queiroz College of Agriculture).

After WWII the government tried, through the IAA, to administer the conflict between the weakened Northeast region and the ascending Southeast, introducing separate quotas and defining production for each region with a view to specific markets. This culminated in the following arrangement: the sugar produced in São Paulo was to supply the Center-South, while the Northeast was to keep the more profitable external market (Szmrecsányi and Ramos, 2006).

The international market for sugar recovered from the sixties and in 1971 the government launched a program to rationalize the sugar industry through the IAA. It also launched a national sugarcane breeding program (Planalsucar).

Sugar supply grew significantly during the first half of the seventies, driven by exports. However, sugar prices started to fall in the second part of the decade, just as the national economy was suffering the impact of the oil crisis. The government announced a number of measures to address the problems caused by excessive dependence on oil, more than 80% of which was imported and which quadrupled in price in 1973. One of the government initiatives was to associate potential expansion of the sugarcane industry with the opportunity provided by the oil crisis by launching Proalcool, the National Alcohol Program, in 1975.

The aim of this program was to replace the gasoline consumed on the domestic market with ethanol produced from biomass. Initially the idea was to use more than one crop as raw material (including cassava, for example), but sugarcane soon proved to have the most potential. To boost production the government provided working capital at negative interest rates for the construction or expansion of sugar mills, to which units were added to distill ethanol. Output quintupled from 664,000 m^3 in the 1976/1977 crop year to 3.7 million m^3 in 1980/1981. Soon production of anhydrous ethanol was sufficient for a 15–20% blend with gasoline.

After this first phase, the government embarked on a second investment cycle because of the success in producing ethanol and in response to the second oil crisis in 1979. As a result, production tripled by 1985. This time ethanol was used neat in vehicles with engines designed specifically to run on the fuel. The emergence of a new market for dedicated ethanol vehicles was possible only because the program relied on tax incentives for new vehicles and controlled prices to make ethanol more economical than gasoline. The government induced Petrobras and distributors to create the systems required for storage, transportation and distribution of hydrated ethanol used neat in light vehicles. This set of measures, plus financing for new distilleries, guaranteed strong growth of production in a 5-year period, surpassing the established goal of 10 million m^3 to reach 11.5 million m^3 in 1985, and led to rapid expansion of the nation's fleet fueled by hydrated ethanol.

The success of Proalcool hid important difficulties, such as the need for significant government subsidies for the sugarcane agroindustry in order to assure the expansion of its production capacity. The return of democracy and a worsening economic crisis at home put an end to the government's capacity to allocate significant capital flows to new economic activities considered priorities. The aggravating component in this situation was the so-called oil countershock in the mid-1980s, when oil prices fell worldwide. This rapidly affected the internal market for refined petroleum products including gasoline. The real price of ethanol trended down and at the same time subsidies for new distilleries ceased.

Ethanol production leveled off in the late 1980s, creating an explosive situation. Supply was insufficient to meet demand, which continued to rise because of controlled prices and subsidies for sales of new ethanol-fueled vehicles. The result was a shortage of ethanol for final consumers, and Proalcool lost credibility. Imports of ethanol were necessary in the early 1990s.

The crisis caused by the shortage of ethanol and closure of the IAA by the Collor administration in 1990 marked the end of Proalcool and the beginning of a new stage. Cars fueled by hydrated ethanol, which accounted for 90% of sales in the 1980s, fell very sharply. Ethanol supply and demand balanced out at around 12 million m^3/year throughout the decade. However, situation was inherently unstable for two reasons. The first was a recovery in the domestic market for automotive vehicles, led by entry-class cars with 1000 cc engines that ran on gasoline blended with anhydrous ethanol. On the other hand, sales of new cars fueled by hydrated ethanol remained very low and the existing fleet was not renewed. During this decade these two phenomena offset each other: the drop in consumption of hydrated ethanol was counterbalanced by the use of anhydrous ethanol (Fig. 1). At the end of the decade, however, the volume of old ethanol fueled vehicles being scrapped surpassed the production of new ones, threatening the economic viability of more than 25,000 filling stations that comprised the distribution infrastructure created during the second phase of Proalcool.

It is important to note that the relative feebleness of the ethanol market contrasted with the dynamism of the sugarcane industry, which kept growing throughout the decade (Fig. 2) (Furtado and Scandiffio, 2006). This dynamism derived from expansion of the sugar market driven by exports. Between 1992 and 1999, Brazil multiplied its sugar exports fivefold to become the leading world exporter. In 2004 Brazil accounted for 36.2% of world sugar exports. This strong export performance related directly to the dynamism of the sugarcane agroindustry, which produces in mills coupled with distilleries and thus has the option to alternate the production of sugar and ethanol according to the opportunities for expansion offered by these two markets.

The ethanol market has recently resumed growth thanks to a steady rise in domestic prices of petroleum products. Prices of hydrated ethanol have fallen compared to gasoline prices, making ethanol-fueled vehicles an attractive purchase again. Nevertheless, consumers were initially reluctant to buy new ethanol-fueled cars because of negative memories of the ethanol shortage, alongside uncertainty that ethanol prices would always be more advantageous compared with gasoline.[1]

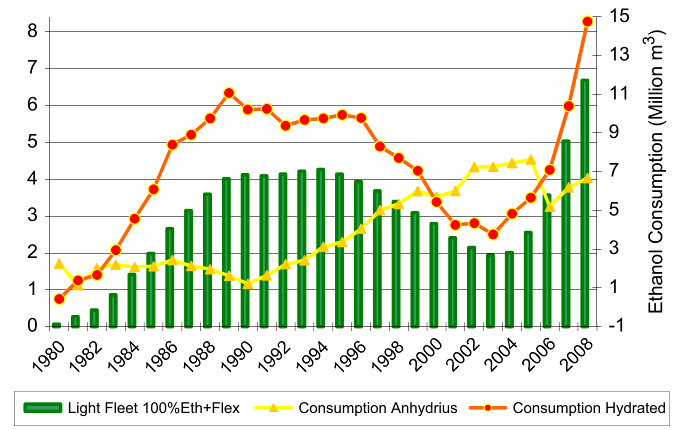

Fig. 1. Evolution of ethanol light fleet cars and ethanol consumption in Brazil (1980–2008).
Source: Anfavea, 2009 and MAPA (Ministry of Agriculture), 2009.

The solution came in 2003 with the introduction of the flexible-fuel vehicle (FFV), which can use in any proportion ethanol or gasoline in the same tank. This gave the consumer a possibility of choice depending on market prices and availability of the two fuels. The success of FFV car sales was soon reflected by hydrated ethanol production, which increased accordingly (Fig. 1). The production of hydrated ethanol dropped to less than 5 million m^3 at the beginning of this decade, but since then started a firm recovery surpassing in 2007–2008 harvest the top level seen in the mid-1990s, driven by attractive internal prices (Fig. 3).

However the recovery in domestic consumption, together with export growth, was enough to create a slight shortage of ethanol in the last period between harvests. To minimize the shortage, the government decided to reduce the ethanol–gasoline blend from 25% to 20%.

4. Leading actors in the Brazilian sugarcane agroindustry innovation system

The expansion of sugarcane production was basically supported by São Paulo State. The sectoral innovation system for sugarcane production tended to expand more dynamically in the richest region of the country. The dynamism of the São Paulo region was based on a combination of several factors, mainly abundant natural resources (land) of good quality, better transport and energy infrastructure, proximity to the largest market, and, above all, a regional system of innovation that brings together producers, capital goods manufacturers, research institutes and universities. A list of the main actors of this Innovation System with their functions and activities can be found in Table 1.

This system enabled São Paulo to increase the sugarcane productivity steadily from plantations located in this same region. For this reason, the Brazilian innovation system for the sugarcane agroindustry is essentially from this region which supports and sustains practically all the relevant institutions that act dynamically in the system. The unique feature of the sugarcane innovation system in São Paulo is the supremacy of private over public research, although it was not always so, contrary to the rest of the agroindustry.

[1] Estimated equilibrium price ethanol/gasoline is 70%.

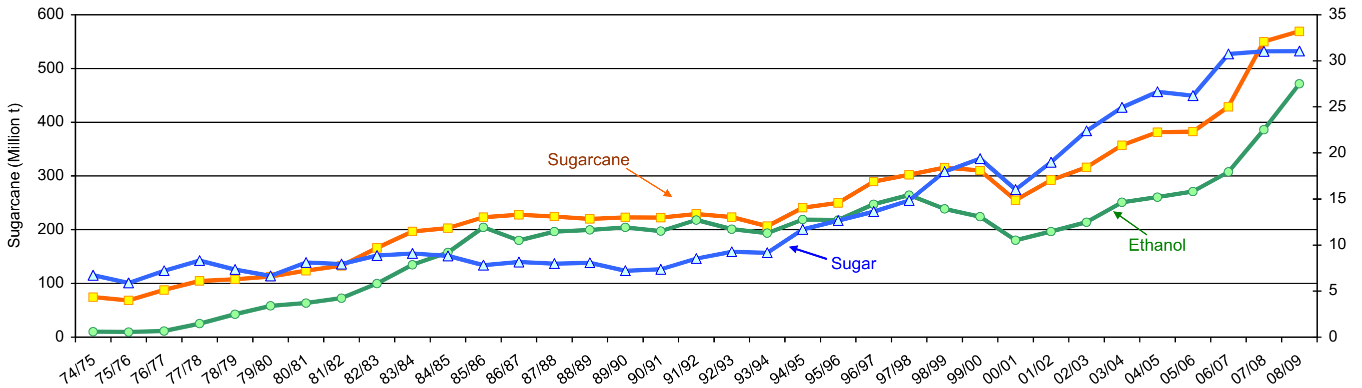

Fig. 2. Evolution of Brazilian production of sugarcane, sugar, and ethanol (1974/1975–2008/2009).
Source: UNICA (Sugarcane Industry Association) and MAPA (Ministry of Agriculture).

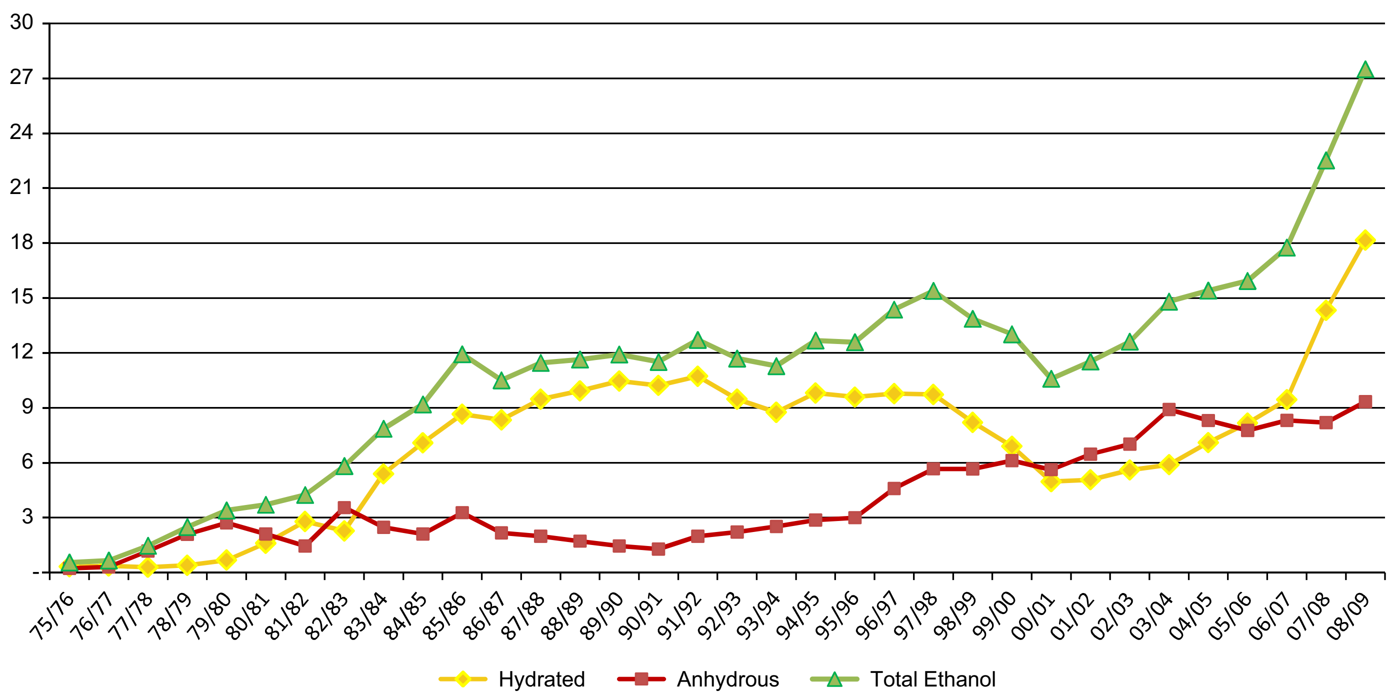

Fig. 3. Brazilian production of ethanol (1975/1976–2008/2009).
Source: UNICA.

Table 1
Main actors of the sugarcane innovation system.

Actors (date of foundation—date of closure)	Institutional nature	Description	Functions	Activities
ESALQ (1901–)	University	State of São Paulo Agronomic School	Human resources traininng and research execution	First agronomic station
IAC (1887–)	Research center	State of São Paulo Agronomic Research Centre	Research execution	7 agronomic stations
IAA (1933–1990)	Federal controlling	Sugar and Alcohol National Institute	Research funding	Production and price planning
Planalsucar (1972–1990)	Research program	National Sugarcane Breeding Program belonging to IAA	Research execution	30 Agronomic stations
Ridesa (1991–)	Research network	University network for development of the sugar–ethanol sector	Research execution	21 agronomic stations
CTC (1970–)	Research center	Sugarcane Technology Center in São Paulo	Research execution	Agronomic research Industrial research
Dedini (1922–)	Firm	Capital goods supplier	Research execution and funding	Industrial research Second generation ethanol
CanaVialis and Alellyx (2004–)	Firm	Start-ups	Research execution	Agronomic and biotechnology research
CTBE	Research center	Brazilian Bioethanol Science and Technology Laboratory	Research execution	Basic research Secong generation ethanol

Brazilian agricultural research is predominantly financed by the public sector. A study conducted by Embrapa (Beintema et al., 2001) estimated that federal research institutions (mostly Embrapa) as well as state research institutions and universities are responsible for 89% of Brazilian research efforts in agriculture. This does not seem to be the situation for the sugarcane sector. The most important sugarcane research center, Centro de Tecnologia Canavieira (CTC), is a private institution. Federal government action has been timid in this area, especially since Planalsucar was shut down as a consequence of the closure of the IAA at the beginning of the Collor administration. Planalsucar conducted research into genetic improvement in several Brazilian states. These activities were partially maintained with the support of the private sector.

The leading players in the São Paulo innovation system do research mainly in agriculture, developing new sugarcane varieties (see Fig. 4). The increase in cane yields, measured by tons per hectare or sugar content, has been obtained by developing new varieties that are better adapted to Brazilian weather and soil, and also more resistant to plant diseases. This improvement enabled ethanol costs to be cut and production increased. However, important advances have also been achieved in the industrial area, such as improving sugar extraction, vinasse recovery, and fermentation, as well as cogeneration of power using bagasse. Alongside research centers, government organizations are also important actors in terms of the funding of innovation and organization of programs. These public organizations belong to the federal sphere and São Paulo State.

The innovation activities of the sugarcane sectoral system were mainly directed towards improving and perfecting the productive system already established by the large sugar mills since the mid-1900s. There was no radical innovation that could drastically change the sugar and ethanol production process. However, productivity gains were significant, enabling Brazil to rank first in the world in terms of production costs, while the use of bagasse dramatically reduced the need for fossil fuels in the industrial process. Thus, thanks mainly to an incremental technological trajectory, Brazilian ethanol from sugarcane became competitive in terms of both cost and environmental sustainability, because of the reduction in greenhouse gas emissions. However, as discussed below, the changes in international technological regimes brought about by the present energy crisis and the challenges of a new low-carbon economy have led to more vigorous efforts to develop appropriate technology, not least in renewable energy, especially in the developed countries. The institutions of the sugarcane sectoral innovation system are trying to cope with these new challenges.

5. The IAC and Esalq

The IAC (Campinas Institute of Agronomy), established in the 19th century, was initially created to support coffee growing in São Paulo State. The need for research emerged only in the 1920s, when sugarcane growing began expanding in São Paulo. In 1924, agricultural production in the state was threatened by fast dissemination of the sugarcane mosaic virus. New more resistant varieties had to be developed to combat mosaic. The São Paulo State Government set up a sugarcane experiment station attached to Esalq (the Luiz de Queiroz College of Agriculture), located in Piracicaba. This enjoyed rapid success (Mariotoni, 2004). The experiment station was transferred to the IAC in the 1930s.

From then on, the IAC led the process of developing new varieties and modernizing the sugarcane crop within the state. Although the IAA had more stations in other states of the country, the São Paulo sugarcane agroindustry became very dynamic, overtaking Pernambuco in the production of sugar for the first time during the 1950s. The favorable situation enjoyed by the IAC began to change in the 1960s, when the São Paulo State Government reduced its funding, and deteriorated in the following decades.

The IAC's importance was not to recover until the second half of the 1990s, with the launching of Procana, an IAC genetic improvement program. This program was to restructure the IAC's research activities on new foundations. The program was

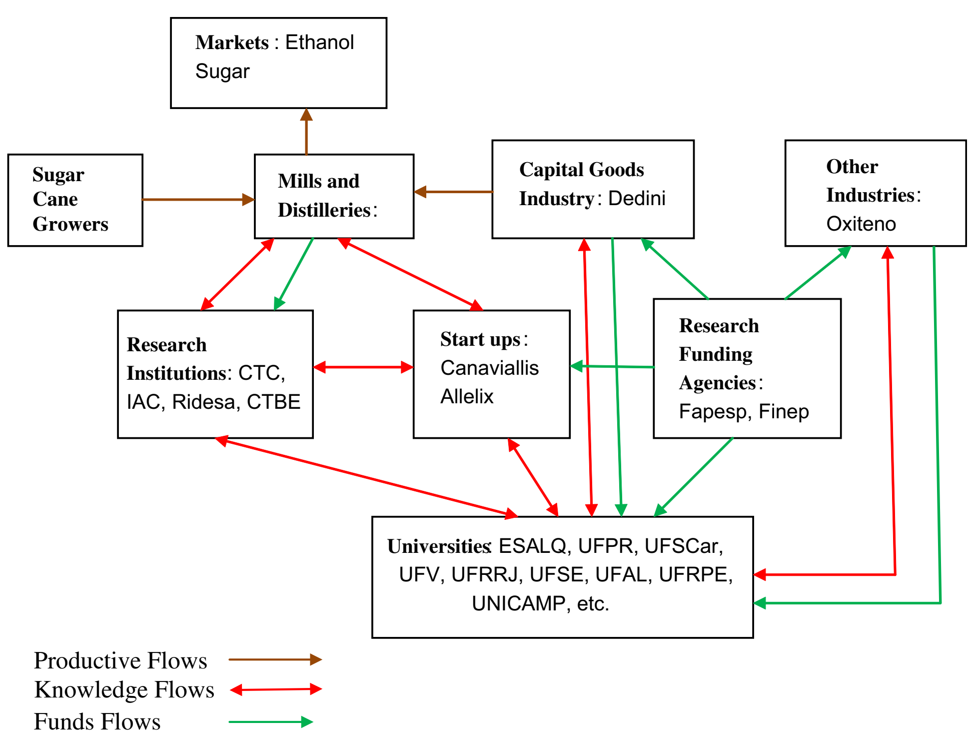

Fig. 4. The Brazilian sugar cane innovation system.

decentralized to include more experiment stations, and received contributions from the private sector. The Procana program has become an important success, not only for the introduction of new varieties, but mainly for its capacity to introduce new agricultural methods for associated mills. The IAC program costs R$2 million per year and is 60% financed by the private sector (Hasegawa, 2005).

6. The National Sugarcane Breeding Program (Planalsucar)

In 1972, Planalsucar (the National Sugarcane Breeding Program) established its headquarters at Piracicaba close to Esalq. The aim was to improve sugarcane yields throughout the country. The program had five experiment stations in São Paulo State. However, it focused on contributing to public research and brought a low economic return for the state. The research conducted at Planalsucar explored the domain of genetic improvement and extended to the industrial process area. It enabled the introduction of technologies for vinasse recycling, which was essential for the environmental feasability of Proalcool. Even so the program's contribution was limited to introducing new varieties of sugarcane in the state of São Paulo (Belik, 1985). In 1984, when the first variety census of São Paulo was realized, 44% of the area under sugarcane in São Paulo used NA varieties from northern Argentina, while 19.4% used IAC varieties, 15.8% SP varieties from Copersucar, and 12.8% CB varieties from the Campos experiment station in Rio de Janeiro State.

Planalsucar played an important role in other states of the country to accommodate modern usages for sugarcane. The program opened 30 stations throughout the country, 14 of them in the central and southern regions. Its contribution was also very important to improve sugarcane productivity in the Northeastern states. There were more experiment stations in the state of Alagoas (Northeast) than in São Paulo.

Planalsucar was dismantled immediately after the IAA's closure in 1990. Its activities were incorporated by Ridesa.

7. University Network for Development of the Sugar–Ethanol Sector (Ridesa)

Ridesa is a network of federal universities created to take over the activities of Planalsucar in sugarcane breeding research. It comprises seven universities (UFPR, UFSCar, UFV, UFRRJ, UFSE, UFAL, and UFRPE) located in the same areas as Planalsucar. Technical staff came from Planalsucar, while infrastructure comprises headquarters with experiment stations acting as coordinating branches. With the support and legally binding collaboration of a significant part of the sugar and ethanol industry, the network started operating in 1991, using Planalsucar's staff and regional bases plus academics from the universities involved.

As sugar-cane breeding is a lengthy process, Ridesa took advantage of Planalsucar's long-term investment. A second variety census conducted in 1994 showed the RB72-454 variety, which started to be developed at the program's inception and was launched in 1982, occupying 26.6% of the acreage under cultivation in São Paulo State.

Ridesa has 21 experiment stations strategically located in seven states where sugarcane is economically important. Besides these, the network also conducts on-campus research at all seven federal universities involved, mainly via master's and doctoral courses. It has recently been enlarged to include three more universities, all located in new areas of sugarcane expansion in the Center-West (UFG, UFPI, and UFMT). The network comprises 142 researchers and 82 technicians.

Ridesa continued the Sugarcane Genetic Improvement Program (PMGCA), and still uses the code RB to identify its cultivars. The PMGCA released 67 varieties, 48 after the closure of Planalsucar. Ridesa achieved significant success in developing varieties and competed with Copersucar in the release of sugarcane varieties. In 2008, RB varieties accounted for 56.9% of sugarcane grown in São Paulo (PMGCA, 2008). However, the most important varieties were developed in the 1980s. Resources for the program are limited and come basically from the private sector.

8. Copersucar Sugarcane Technology Center (CTC)

Copersucar (the acronym for São Paulo Sugarcane Cooperative) was established in 1959 as a merger of two regional cooperatives. It expanded rapidly to win a 51% share of the domestic sugar market (Mariotoni, 2004), but received scant support from the IAA for sugarcane breeding. It wanted to change this situation, which did not help the local agroindustry, and in 1968 invited the Hawaiian geneticist Dr. A.J. Mangelsdorf to structure a program for genetic improvement. This was the basis for the creation of CTC, the Copersucar Research Center.

CTC was set up in 1970 at Piracicaba. Initially it competed with the IAA's experiment stations, which enjoyed more favorable conditions than CTC. Technical assistance for the associated mills soon became an important source of revenue for CTC. This experience with mill maintenance was to define its role as a leader in industrial process innovations.

The technological capability of the Brazilian capital goods industry was poor during the period before Proalcool. When significant amounts were invested via Proalcool, the technology embodied in equipment was obsolete. CTC's function was basically to introduce incremental innovations that improved the efficiency of sugar extraction from cane and fermentation from cane syrup. These innovations increased the level of sugar extraction from 92% before Proalcool to 96% in the mid-1980s (Mariotoni, 2004).

The breeding program began yielding good results in the 1980s. The varieties used in São Paulo that had come from other states and Argentina began to be replaced with new varieties developed by CTC. In the early 1990s, CTC's varieties became predominant in São Paulo, accounting for 65.7% of the acreage.

In spite of CTC's great success, Copersucar faced growing financial problems mostly due to strong fluctuation in international commodity prices, and its members were reluctant to finance research. As a result, the number of members, which exceeded 70 mills during Copersucar's halcyon years, fell below 40 at the end of 1990s. The technologies developed by CTC, albeit extremely important to assure profitability and steadily rising yields for the industry, were easily appropriated by non-members. Copersucar ended up dissolving CTC, which became the Sugarcane Technology Center, in 2005.

The breeding program lost its leadership to Ridesa during the present decade. SP and CTC varieties accounted for 38% of total acreage in 2008 (PMGCA, 2008).

CTC is now a private institution with a budget of R$30 million and 150 researchers.

9. Capital goods industry—the Dedini case

The capital goods industry associated with the sugarcane agroindustry emerged basically within the state of São Paulo. The leading manufacturer is Dedini S.A., which supplies industrial equipment to most mills and distilleries. Founded in the 1920s in Piracicaba to provide maintenance services for sugar mills, Dedini

Table 2
Dedini's applications for patents and utility models.
Source: INPI, 2009.

	1980–1989	1990–1999	2000–2008
Patents	28	7	14
Utility models	12	3	0

began producing complete mills under the turnkey system in the 1930s as Brazil increasingly industrialized.

In 2008 Dedini reported net sales of R$1.8 billion, with exports accounting for R$239 million. It then had 5860 employees. It produces capital goods for several markets, of which sugar and ethanol are the most important.

Sugar production technology changed very little until the advent of Proalcool, and was mostly public property. However, Proalcool created growing technological demand for incremental innovations, especially in São Paulo agroindustry, and Dedini changed its technological profile as a result. Between 1980 and May 2008, Dedini deposited 64 patent and utility model applications with INPI, the National Institute for Industrial Property. A quantitative analysis of these applications shows that patent activity was very intense during the 1980s, i.e. during the Proalcool period, declining sharply in the 1990s. Only at the beginning of this decade did growth in patent activity resume, albeit at a slower pace (Table 2).

Dedini has received support from the São Paulo State Research Foundation (Fapesp) to build a large-scale pilot plant to produce ethanol from sugarcane bagasse using its patented hydrolysis process. The process, called DHR, is an important opportunity for the Brazilian industry to develop technology to produce ethanol from sugarcane by hydrolysis.

10. CanaVialis and Alellyx

Votorantim Ventures, a leading venture capital fund, invested R$25 million in 2003 to fund a biotechnology company called CanaVialis. The company was formed by a research group from the Federal University of São Carlos with substantial experience in sugarcane breeding. They had participated in Planalsucar's sugarcane breeding program during the 1970s and now formed this company with the express goal of moving from the traditional model of sugarcane genetic improvement to a new one based on biotechnology. However, the company also kept one foot in traditional breeding technologies for the development of new varieties. A second company named Alellyx was set up in 2002, also with support from Votorantim Ventures.

CanaVialis has two experiment stations, one in São Paulo and the other in Paraná, as well as a Breeding Center for crossing and seedling production in Alagoas. This infrastructure is a legacy from Planalsucar. The company has signed contracts with 34 mills, almost half of which belong to Cosan, Brazil's largest sugar and ethanol group. CanaVialis operates an area of 593,000 ha producing 54 million metric tons of sugarcane, equivalent to 5.2 million tons of sugar or 1.8 million m^3 of ethanol.[2] Its breeding program is considered the largest in the world today, obtaining 1.5 million seedlings/year from hybrid seeds produced in its own crossing station at Maceió, Alagoas.

Also initially funded by Votorantim, Alellyx is dedicated specifically to genetic research, but goes beyond sugarcane to include oranges and eucalyptus. In partnership with CanaVialis, Alellyx researches new varieties, which are developed with the use of biotechnology. According to *Valor Econômico*, a leading business daily, the two companies invest some US$40 million/year. Their goal is to use genetic engineering to develop varieties with better yields and improved resistance to drought and pests. The Alellyx research team comprises 110 professionals, 22 of whom have doctorates and 17 master's degrees.

In 2008 CanaVialis received some R$20 million from FINEP, the Brazilian Innovation Agency, to develop a research kit for molecular markers for sugarcane and other plant varieties, while Alellyx received R$5 million to develop genetically modified sugarcane varieties.

Votorantim lost more than R$2 billion in late 2008, owing to miscalculation in its currency hedging strategy. To cope with this unexpected loss, the group decided to sell Alellyx and CanaVialis to Monsanto for US$290 million. Monsanto, a leader in GM soya and corn seeds, saw the acquisition as an attractive opportunity to penetrate the promising sugarcane business.

Monsanto's acquisition of Alellyx and CanaVialis caused acute stress in the Brazilian sugar community and among the main actors in national science and technology policy. In April 2009, CanaVialis had several thousand sugar plants seized after Ridesa accused the Monsanto-owned biotech firm of reproducing its varieties without authorization or payment of royalties on its intellectual property (Simões, 2009).

11. Brazilian Bioethanol Science and Technology Laboratory

In 2005, a prospective study conducted by a group of researchers at the University of Campinas under the leadership of Prof. Rogério Cerqueira Leite, an important leader of the Brazilian scientific community, indicated that Brazil could become a major exporter of ethanol at the world level supplying between 5% and 10% of world demand over a 20-year period (CGEE, 2009; Leite et al., 2009; NIPE, 2005). One of the main conclusions of this study referred to the role of science and technology research if Brazil wanted to keep its competitive edge in the ethanol industry. Important efforts had to be made, especially in second-generation ethanol technologies. Based on the findings of this study, in 2008 the Brazilian Ministry of Science and Technology decided to create a research center dedicated to ethanol called CTBE near the University of Campinas in São Paulo State.

CTBE's 7900 m^2 infrastructure houses a permanent staff of 50 researchers and up to 80 visiting researchers. It will operate effectively by mid-2010. Its mission is to contribute to ensuring Brazilian leadership in the sustainable production of bioethanol from sugarcane through state-of-the-art RD&I. The main research programs are a pilot plant for process development, especially for hydrolysis research (industrial), low-impact mechanization without burning for no-till farming of sugarcane (agriculture), impact of new technologies on sustainability, basic science research, and a virtual biorefinery to evaluate new technologies.

12. Research funding agencies

Since the IAA's closure there has been a significant reduction in support from public agencies for sugarcane R&D. Sectoral Funds (Fundos Setoriais) created from 1999 to supply some needs emerged as a consequence of neoliberal reforms that partially destroyed the Brazilian innovation system during this decade. However, none of these Funds act specifically in the sugarcane arena. A survey of the Prossiga[3] database shows that only 81 of all projects in the database, or 0.5%, return the keyword "sugarcane" (Table 3).

[2] Valor Econômico newspaper, September 6, 2006.

[3] Prossiga is the Brazilian government's Science, Technology and Innovation Information Management Program.

However, a major shift in federal science and technology policy has taken place since 2006. In that year FINEP launched the first round of a special program of grants to fund innovation by firms, amounting to R$300 million. The second and third rounds followed in 2007 and in 2008, respectively, with the latter amounting to R$450 million. The projects involved innovation in areas such as information technology, nanotechnology, aerospace technology, biofuels and energy, and social development. Projects for sugarcane and ethanol received R$65 million in rounds two and three, an important share of the total. This suggests that a qualitative change is happening in federal ethanol innovation policy, as indicated by Table 4.

On the other hand, Fapesp has shown great concern with the sugarcane sector for far longer than the federal government. For example, it supported the Cane Genome project as a part of a broader genomics program. This project began in 1998 and has already identified 50,000 cane genes. It is a remarkable example of the productive use of public resources with intense participation by universities and public institutes in the execution of targeted basic research. It is possible that there is a strong correlation between the amounts of capital allocated by Fapesp and the competitiveness of the sugar and ethanol sector in São Paulo. Fapesp's programs are important initiatives and supported the first steps taken by Alellyx and CanaVialis in the biotechnology arena.

Table 3
Projects of Sectoral Funds (1999–2006).
Source: Based on Prossiga data, extracted December 22, 2006.

Funds	Keyword: biomass	Keyword: sugarcane	All
CT—Energ	46	14	1661
CT—Agronegócio	5	6	1295
CT—Hidro	4	21	1776
CT—Petro	2	7	2932
CT—Infra	1		
CT—Verde e Amarelo	1	3	
CT—Transversais	1	7	1376
CT—Info	1	9	2769
CT—Biotecnologia		3	261
CT—Saúde		7	1137
CT—Mineral			265
CT—Transporte			67
CT—Amazônia			61
CT—Aeronáutico			51
CT—Espacial			33
CT—Funttel		4	33
CT—Aquaviário			7
Total	**61**	**81**	**14.779**

13. The interactive dynamism of the sugarcane agroindustry innovation system

Players in the sugar agroindustry innovation system have shown an important ability to interact, but these initiatives have occurred mostly outside the public sector since the 1990s, contrary to the rest of agriculture where public research prevails. The presence of the private sector is a central aspect of the existing interaction in the sugarcane system, occurring both on the problem-solving side and in the financing and execution of research.

The first form of interaction consisted of cooperation between CTC researchers in industrial processes and the capital goods industry after Proalcool. The pressure roll and Donnelly chute (mill feed) technologies were transferred and adapted by CTC and then sent to capital goods manufacturers in Brazil. These technologies significantly enhanced cane juice extraction efficiency.

As CTC consolidated its position as an important center for generating technological knowledge for the sector, there was growing participation by other players in the innovation process. As an example of CTC's importance, it is worth mentioning the development of biopolymer technology in the 1990s, in cooperation with the São Paulo State Technological Research Institute (IPT). The CTC was also very important for cooperation in the agronomic research field. IAC's sugarcane program has collaborated with CTC in the development of new varieties and uses CTC's experiment station to cross new seedlings.

Ridesa, the network that inherited Planalsucar, illustrates the intense interaction between the agronomic research produced by the universities and the industry, which significantly sponsors the program. The same engagement can be seen in the case of IAC's sugarcane program, which is supported by private initiatives, mainly partner mills, but also sugarcane growers and cooperatives, to finance research activities.

The kind of system constituted after the decline of state intervention in the sector displays a leading presence of the private sector in research funding and the application of new technologies. This model proved remarkably dynamic and

Table 4
FINEP Grants for sugarcane and ethanol projects in 2007 and 2008.
Source: FINEP, http://www.finep.gov.br//fundos_setoriais/subvencao_economica/subvencao_economica_resultado.asp?codSessao=8&codFundo=24; accessed August 30, 2009.

Round	Project title	Firm	Size	Location	Grant (R$)
01/2008	Agrocys for traceability of sugar cane crop	PCG	Medium	Pernambuco	1,263,495
01/2008	Molecular markers for sugar cane	CanaVialis	Small	São Paulo	19,907,800
01/2008	Genetically modified sugar cane	Alellyx	Micro	São Paulo	5,010,000
01/2008	Pirolytic ethanol production	Silton	Micro	Pernambuco	1,393,802
01/2008	Crop system for sugar cane straw harvesting	Delatamaq	Micro	Rio Grande do Sul	971,520
01/2008	Crop system for sugar cane harvesting	Siltomaq	Medium	São Paulo	5,240,227
01/2008	Fluid Bed gasifier for sugar cane biomass	Conventos	Small	Santa Catarina	1,002,000
01/2008	Nitrogen Injection on ethanol vinasse	Enalta	Small	São Paulo	2,683,100
01/2008	Electricity generation from gasifier using bagasse and straw	Orienta	Micro	Espirito Santo	1,554,000
01/2008	Hydrolysis process	Hidrolisis	Micro	São Paulo	1,000,000
01/2007	Sugar cane disease control	Bioenergia	Medium	São Paulo	500,000
01/2007	Genetically modified sugar cane	Alellyx	Micro	São Paulo	9,451,328
01/2007	Sugar cane small scale harvester	Montana	Large	Paraná	4,544,408
01/2007	Fermentation optimization	Usina Cerradinho	Large	São Paulo	562,200
01/2007	Optimization of ethanol production process	Dedini	Large	São Paulo	2,550,000
01/2007	Airplane kerosene from ethanol biomass	Biocapital	Large	Minas Gerais	7,856,000
Total					**65,489,880**

enabled sugarcane growing to expand regularly, both for sugar and ethanol production.

Until recently the sector's evolution was driven by the remaining elements of the productive base formed during the statist period, above all thanks to Proalcool. Interaction between the private and public sectors prevented loss of competencies. On the contrary, public agronomic research was reorganized and increased its capacity to solve problems and transfer technology to the productive sector. However, this interaction is associated only with incremental innovation and is therefore unable to address the emerging technological challenges of bioethanol.

Demand from the domestic market and export expectations pose an even more daunting challenge. The external market itself has enormous potential for expansion. If Brazil were to substitute ethanol for 5% of world demand for gasoline within 20 years, its sugarcane production would have to quadruple, although both volume grown and acreage to meet this goal could be reduced with the introduction of new technologies. The productive leap for sugarcane production that Brazil foresees will disrupt the technological path followed by the sugar and ethanol agroindustry hitherto.

Fapesp has responded positively to this need, sponsoring projects on disruptive technologies that combine public and private research. Besides the cane network mentioned above, Fapesp financed the pilot-scale industrialization of the rapid acid hydrolysis process patented by Dedini. This project is a partnership between CTC and Dedini under Fapesp's PITE Program, which started in 2002. More recently, Fapesp consolidated its leadership in the coordination of technological innovation efforts for the sugarcane sector, pursuing the implementation of a program for the development of sugarcane technology and its byproducts. As a first initiative under this program, Fapesp and Oxiteno, a chemicals company, launched a call for research projects in both acid and enzymatic hydrolysis. The projects will be executed by research institutions in São Paulo State and financed by Fapesp and Oxiteno in accordance with the established principles of the PITE Program. A second initiative was launched with Dedini to develop acid hydrolysis or new related technologies, electricity production from sugarcane byproducts, energy efficiency in the industrial process, and efficiency gains in the distillation and fermentation processes. The Dedini-Fapesp collaboration project will invest R$100 million, with each contributing half, over a 5-year period to finance industry–university research partnerships.

More recently, Fapesp launched the Bioen program to promote ethanol technologies. The program has five main goals. The first is to promote genetic improvement of sugarcane varieties. The second is the ethanol production process. The third is the use of ethanol in car engines. The fourth is research in biorefineries and alcohol chemistry, and the fifth focuses on the social and environmental impacts of biofuels. The amount available for grants totals R$38 million, half from Fapesp and the other half from federal agencies, mainly CNPQ (the National Research Council) and Pronex, an agency of the Ministry of Science and Technology.

14. Final comments

This paper pinpoints that the constitution of a sectoral innovation system had a central role in the success of ethanol in Brazil. It also revealed that this innovation system and its institutional set up evolved during the time, allowing it to cope with the major technological, economic and institutional challenges which emerged when ethanol became a real alternative to fossil fuels. In fact, the sugarcane sectoral innovation system was shaped in São Paulo, when leadership in sugarcane production was gradually transferred from the Northeast region to that state. The federal government was prominent in the development of the sector's economic activity through the IAA and Proalcool programs. Modernization of sugar and ethanol plants was extensively supported by IAA resources, and Proalcool mobilized an unprecedented volume of investment at subsidized interest rates.

With regard to innovation, Planalsucar was an important step in the creation of a research base for the sector, as well as modernizing agricultural practices. Before this, IAC played a noteworthy role in the development of agronomic research in São Paulo. Fortunately the crisis of this model, which crystallized with the IAA's closure in the early 1990s, did not represent the collapse of that system. On the contrary, private actors in the sectoral innovation system responded dynamically, increasing expenditure and participation in R&D. This major engagement increased efficiency and interactivity in the innovation system. However, this is consistent with the technological path driven by incremental innovation, successfully increasing productivity and production on the existing technological base.

The challenges posed by the prospect of expansion in ethanol production are much greater. The displacement of sugarcane production to other states aside from São Paulo, the prevalence of ethanol production over sugar, and above all the need for even greater growth in productivity pose technological challenges that cannot be met by initiatives supported by financial resources from private players alone, not least because the weak appropriation of CTC's research results (gains) has recently derived in its separation from Copersucar.

This new stage of the sugarcane agroindustry innovation system is responsible for reassuming leadership of the public sector, in both financing and coordination to guarantee achievement of the targets for medium- and long-term growth of production. The state of São Paulo is playing this role through Fapesp's Bioen program targeting innovation in bioethanol.

The federal government has recently focused on increasing the innovation effort. Its new funding line through FINEP's grant program has been decisive for several new start-ups, such as Alellyx and CanaVialis. The creation of CTBE is an important step to help the Brazilian sugarcane industry improve its scientific base in order to face the major challenges of second-generation ethanol technologies.

Nevertheless, given the national dimension of the challenges posed by sugarcane expansion, and the scientific and technological challenge of second-generation ethanol, there are some missing steps in the Brazilian innovation system. Monsanto's acquisition of Alellyx and CanaVialis is surely a step back in the evolution of this system. On the other hand, the drive to diffuse new sugarcane varieties in the Center-West's new producing regions is mostly limited to Ridesa. Fapesp and the federal government are focusing more on second-generation technologies. However, the technological challenges posed by these new technologies are huge, and the resources allotted by the United States and Europe are even larger.

Several aspects referring to dynamics of the sugar cane sectoral innovation system need to be better understood, which requires further studies. The capacity of the Brazilian industrial firm to cope with the challenges of the second generation biofuels, with biotechnologies in the development of sugarcane varieties, and with a biochemichal route needs to be evaluated. The industry–university relation will become increasingly important to forward the innovation function of the Brazilian sectoral system. More evidences from others renewable energy innovation systems in developing countries would contribute to improve our understanding about the nature technological change in this socioeconomic context.

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