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Adoption and use of precision agriculture technologies in the sugarcane industry of São Paulo state, Brazil

Claudia Brito Silva · Márcia Azanha Ferraz Dias de Moraes · José Paulo Molin

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Abstract Precision agriculture (PA) technologies are being applied to crops in Brazil, which are important to ensure Brazil's position in agricultural production. However, there are no studies available at present to indicate the extent to which PA technologies are being used in the country. Therefore, the main objective of this research was to investigate how the sugar-ethanol industry in São Paulo state, which produces 60% of the domestic sugarcane, is adopting and using these techniques. For this purpose, primary data were used, which were obtained from a questionnaire sent to all companies operating in the sugar-ethanol industry in the region. The aim was to determine to what extent these companies are adopting and using PA technologies, and also to promote a more in-depth discussion of the topic within the sugar-ethanol industry. Information was obtained on the features of the companies, on sources of information that they use for adopting these technologies, on their impacts on these companies and on obstacles hindering their adoption. The main conclusions of this research suggest that companies that adopt and use PA practices reap benefits, such as managerial improvements, higher yields, lower costs, minimization of environmental impacts and improvements in sugarcane quality.

Keywords Ethanol · Sugar · Sugarcane · Survey · Brazil

C. B. Silva · M. A. F. D. de Moraes (✉)
Economic, Business Administration and Sociology Department, Luiz de Queiroz College of Agriculture, University of São Paulo, Av. Pádua Dias, 11. São Dimas, mailbox 9, Piracicaba, SP 13418-900, Brazil
e-mail: mafdmora@esalq.usp.br
URL: http://esalq.usp.br

C. B. Silva
e-mail: cloubrito@hotmail.com

J. P. Molin
Biosystems Engineering Department, Luiz de Queiroz College of Agriculture, University of São Paulo, Av. Pádua Dias, 11. São Dimas, mailbox 9, Piracicaba, SP 13418-900, Brazil
e-mail: jpmolin@esalq.usp.br
URL: http://esalq.usp.br

Introduction

Brazil is the largest sugarcane producer in the world; 495 million metric tons were processed from the 2007–2008 harvest, according to data from the Ministry of Agriculture, Livestock and Supply (2009). Sugarcane is grown in much of Brazil, but São Paulo state produces the most. It accounts for 60% of domestic production in the country and there are 205 processing plants. As a result of its geographic location and large land area, Brazil produces sugarcane throughout the year and has two distinct harvest periods. Plants in the north and northeast regions harvest sugarcane between September and April, whereas those in the southeastern, southern and central-west regions harvest it from April until November.

Of the 6.96 million hectares planted with sugarcane for the 2007–2008 harvest, 80% were in the center-south region with the remaining 20% in the north-northeast. Average yield in the center-south region is greater than in the north-northeast region, 83 t ha^{-1} and 61 t ha^{-1}, respectively, for the 2007–2008 harvest (National Food Supply Company 2007). The greater production in the center-south region can be largely explained by its weather and topography, which are more suitable for growing sugarcane.

Most sugarcane processing plants in Brazil produce sugar and ethanol, some produce only sugar, whereas the distilleries produce only ethanol. According to Ministry of Agriculture, Livestock and Supply (2009) 59% of all Brazilian plants are sugar and ethanol producing units, 37% are ethanol distilleries and the remaining 4% produce sugar only.

Brazil is the world leader in the production and export of sugar and ethanol. In 2008, 19.7 million metric tons of sugar and 4.8 billion liters of ethanol were exported (Ministry of Agriculture, Livestock and Supply 2009). Because of a significant increase in the domestic fleet of flex-fuel driven vehicles, which can use both ethanol and gasoline at any blend level, ethanol from sugarcane emerged as one of the most competitive alternative fuels in the world. Compared to other sources, it is a clean and renewable source of energy that can offset carbon emissions from fossil fuels. As a result, ethanol exports are expected to increase significantly in the future.

The sugarcane expansion of the last 25 years has occurred primarily in south-central Brazil, in areas that are far from both from the Amazon rainforest and the Pantanal wetlands, which are both of ecological importance in Brazil (see Fig. 1). The rainforest does not provide appropriate economic and agronomic conditions for sugarcane production (that is the alternating dry and wet seasons needed to grow the plant and build up sucrose levels in the cane) (Macedo 2007).

Brazil also has enough available agricultural land to expand sugarcane production with no impact on national food production. According to estimates of the Brazilian Institute for Geography and Statistics (2009) in 2007, the sugarcane area occupied about 7.8 million hectares, which represents 0.9% of the total land of the country and 2.3% of the national arable land. The available land for expansion of both agriculture and livestock in 2007 was 77 million hectares. Therefore, expansion of the sugarcane sector will not cause negative impacts on the production of other crops and cattle.

The costs of producing sugar are the lowest in the world. According to Macedo (2007) the production cost for the more efficient mills in the southeastern, southern and central-west regions at the end of the 2005–2006 season was US$ 125 t^{-1} of sugar. According to this author, LMC International[1] estimate the cost of sugar for the northeast region as US$ 220 t^{-1}. The costs of producing ethanol from sugarcane are less than those of

[1] LMC International is a privately owned company, with offices in Oxford, New York and Kuala Lumpur. In Latin America LMC international works closely with a partner organisation, Canaplan, in Sao Paolo.

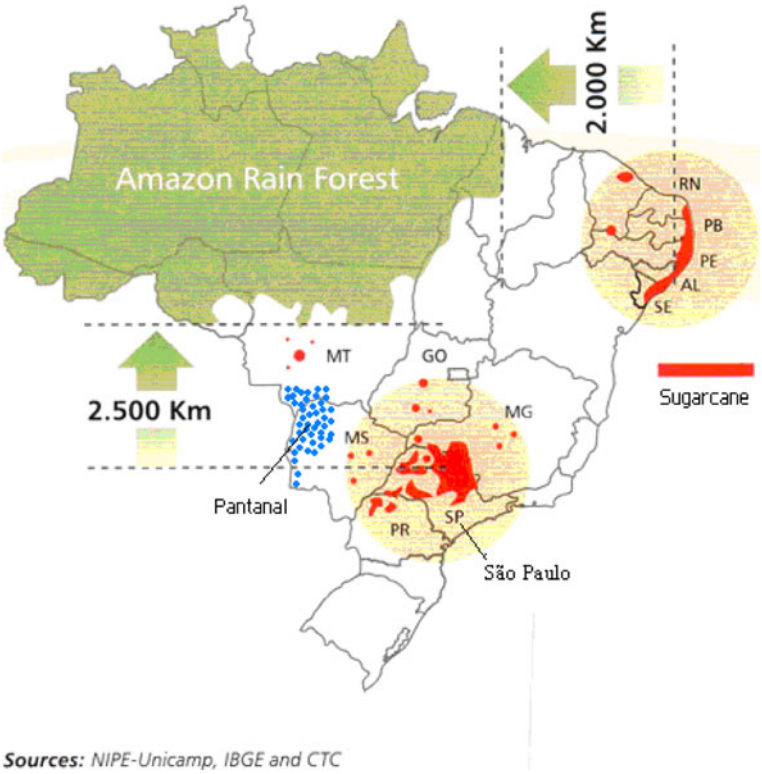

Fig. 1 Location of sugarcane producing regions in Brazil

producing ethanol from corn in the USA or from wheat and sugar beet in Europe. Macedo (2007) indicated that the cost of ethanol from Brazilian sugarcane at the end of the 2005–2006 season was US$0.23 l^{-1}, whereas it was about US$ 0.33 l^{-1} for corn ethanol in the United States and US$0.48 l^{-1} and US$ 0.52 l^{-1} for wheat and sugar beet ethanol, respectively, in Europe. According to Macedo (2007) the low costs in Brazil are the result of advances in productivity sustained by investments in production, logistics and the adoption of new technologies, including PA. The author points out that several improvements were made in sugarcane, ethanol and sugar production, namely: the introduction of new sugarcane varieties, optimization of sugarcane operations (such as transport), integrated sugarcane and waste harvesting and the transport system, better agronomic controls, fermentation and grinding, use of vinasse as a fertilizer, biological control of the sugarcane beetle, improvement in the technical management of industrial production and maintenance, greater industrial automation, new separation processes (juice and downstream processing), energy independence, among others. In addition, the author points out that genetic modification of sugarcane is advancing rapidly in Brazil (for more detail see Macedo 2007).

Footnote 1 continued
LMC International is the leading independent economic and business consultancy for the agribusiness sector around the world.

Yield maps are the key for managing crops in terms of spatial variation. The supply of yield monitors for sugarcane is still almost nonexistent; this type of equipment on harvesters has appeared on the market only recently (Magalhães and Cerri 2007). According to Lino (2009), in Sao Paulo state about 60% of the sugarcane was harvested mechanically in the 2008–2009 season.

Automatic pilot technology has been successfully adapted to sugarcane agriculture. Traditionally, the tractor would be driven more or less 'by sight' to where the cane was either to be planted or cut, whereas the automatic pilot system does this with precision and benefits users in other ways. The automatic pilot enables a reduction in soil compaction, improved control of vehicle traffic including increased speed of the tractor, planter or harvester, and consequently higher productivity, less operator fatigue, 24-h operation and lower fuel costs, among others. Harvesting is done annually and the planting is done only every 5 years, and there are different benefits from PA that are unique to each activity.

Although PA is being adopted increasingly in Brazil, no studies are available at present on the process of adopting and using PA technologies in the country, whereas in the USA it has been studied by several researchers. Whipker and Akridge (2008) examined the adoption of PA practices in 2500 retail crop input dealerships across the USA. Dealers were asked questions about the types of precision services they offer and or use in their businesses, the fees they charge for precision services, how their customers adopt PA practices and how profitable they are. Of the dealers surveyed, 61% offered some type of precision service. Dealerships owned by cooperatives and regional or national organizations were more likely to offer precision services than independent dealerships. Forty-three percent of the respondents thought that they made a profit on their precision services, whereas some 30% believed they broke even, covering only the fixed and variable costs of offering the services. Dealers continued to expect growth in precision services, and this growth was more substantial in the Midwest relative to other states. Griffin et al. (2004) investigated data on the adoption of PA technology in the USA, and according to this study about 90% of the world's yield monitors are there.

A mail survey of cotton producers was conducted in the six-state region of Alabama, Florida, Georgia, Mississippi, North Carolina and Tennessee. Twenty-three percent of respondents had used at least one from of PA technology. The most common technologies were soil sampling on a grid or by management zone, variable-rate lime application, plant tissue testing, soil survey maps, and variable-rate phosphorous and potassium application. Profit and environmental benefits were the most influential factors in a producer's decision to adopt PA technologies, whereas extension or university personnel, crop consultants and farm dealers provided the most help in learning about these technologies. Eighty-five percent of adopters and 63% of non-adopters thought PA would be profitable for them to use in the future (Roberts et al. 2001).

There are few published studies that provide data on the adoption of PA. Bramley and Quabba (2001) reviewed the results of two seasons of sugarcane yield mapping in Australia and concluded that sugarcane production is ideally suited to the adoption of PA. For this to be successful, significant changes to current Australian practices may be required, especially with respect to harvest management. Bramley (2009) reviewed PA research and adoption around the world and considered that it is ideally suited to sugarcane production, although it has not yet been adopted by Australian sugarcane producers, apart from for specific technologies such as automatic pilots for controlled traffic. Maohua (2001) described some developments in China, and Fountas et al. (2005) provided a comparison on the current status of the use of PA in Denmark and the Eastern Corn Belt, USA.

There are no studies on the current use of PA practices in Brazil. Therefore, the objective of this research was to determine the degree of adoption and use of PA technologies, which have been used most in plants and distilleries in São Paulo state, in addition to collecting information on the features of sugar-ethanol companies, the impacts of PA technologies, information sources used for implementing these technologies and obstacles that affect their adoption.

Materials and methods

The data used in this paper were primary data, that is data obtained from questionnaires returned by managers of the sugar-ethanol industry in São Paulo state (Fig. 1) which have their own sugarcane plantations. Although the survey recognized the existence of independent sugarcane farmers who grow approximately 25% of the sugarcane produced in Brazil, it was focused on vertically integrated sugar and ethanol companies.

The period analyzed in this study is 2008 and it included all sugar mills and distilleries in São Paulo state. The list of sugar and ethanol producing units was obtained from the website of the Union of Bioenergy Producers—UDOP, whose portal offers a list of names, addresses, telephone numbers and e-mail addresses of all plants and distilleries in the state. To ensure the quality of information at the data collection phase, some fundamental procedures were adopted. The first step was to identify the agricultural director or manager of each plant or distillery who was sufficiently familiar with PA concepts and was assumed to have the technical skills to provide the required information. It should be emphasized that identifying the agricultural directors or managers was an important part of this survey because the questions required personnel with specialized skills, decision-making authority in the company and who could also provide the necessary data. Once this person was identified in each plant or distillery, he or she was asked by telephone to fill out the questionnaire. The questionnaires were then returned electronically by the respondents.

The logical framework of the questionnaire on the adoption and use of PA technology was divided into sections according to topics, Fig. 2.

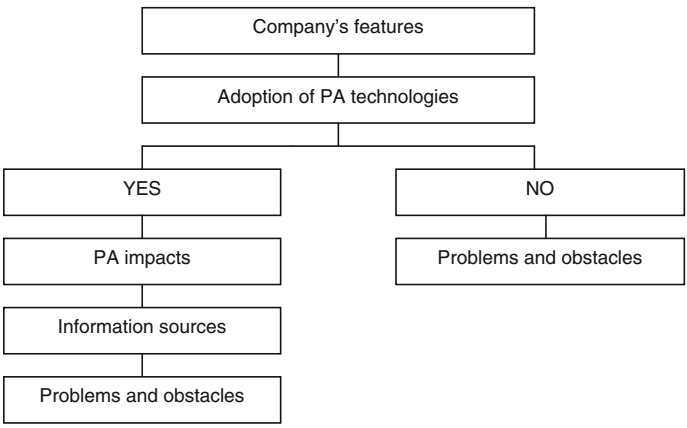

Fig. 2 Structure of the survey questionnaire

The objectives and definitions of the variables for each of the themed sections of the questionnaire are given below.

Characteristics of the companies

To understand some relevant aspects of the relationship between PA adoption and features of the company, some variables were included in the questionnaire to identify: the origin of the company's controlling equity; whether the company belonged to a corporate group or was an independent company; whether the company was professionally managed or family-run; the total amount of sugarcane crushed (in metric tons) from the 2007–2008 harvest; total area (owned by the company and or leased) planted with sugarcane in hectares; number of people employed in the company's agricultural activities; the financing structure of the company's expenditure; whether it was an exporting company or not.

Use of PA technologies

In this section, the companies were asked to answer four questions: whether they adopted PA or not and which technologies related to it they had been using; for how many years they had been used by the company; whether they had plans to expand, maintain or reduce PA use over the next 5 years and whether the company hired, fully or partially, PA services provided by third parties.

PA impacts

This section of the questionnaire was intended to identify impacts associated with PA use such as: significant changes in management; improvements in sugarcane quality; increases in productivity; reduction of production costs; fewer impacts on the environment; increase in the company's market share and compliance with regulations related to the domestic and international market.

PA adoption information sources

The plants and distilleries can get guidance on how to adopt PA from various information sources and their propensity to adopt it is certainly influenced by their capacity to absorb and combine these sources. Therefore, identifying sources of information used in the process of adopting PA can be an indicator of the process by which the new technology is being disseminated and absorbed. This section identified the importance of sources of information generated within the companies by, for example, their R&D department and other units, and those obtained from external sources (corporate and educational sources and research institutions), such as another company of the group; machine, equipment, component or software vendors; competitors; consultancy firms and independent consultants; universities and research institutes; specialized conferences, meetings and publications; and fairs and exhibitions.

Problems and obstacles affecting the adoption of PA technologies

This section of the questionnaire was designed to identify the reasons that led the plant or distillery not to adopt PA technologies. For the companies that adopted PA, it allowed for information on difficulties or obstacles in implementing it to be collected. A list of

problems and obstacles related to the associated technologies was submitted to both plants and distilleries that adopt PA and to those that do not, and both were asked to indicate the importance of each of them.

Results and discussion

The response rate was satisfactory, as 87 of the 205 plants or distilleries operating in the region returned the questionnaire in full for 2008, or 42% of the sugar–ethanol companies that are active in São Paulo state. In this state, 205 plants and distilleries processed 296 million tons from the 2007–2008 sugarcane harvest. Worthy of mention is the fact that the 87 plants or distilleries that returned the questionnaire processed about 170 million tons in the same harvest, which is 57% of the total regional production.

Responses were analyzed statistically and the results are given in Tables 1, 2, 3 and 4. A *t*-test, Wilcoxon test and Fisher's exact test were used to compare responses between adopters and non-adopters of PA technologies. Table 1 shows the degree of PA adoption and variables for the size (production, area and workers) of the plants or distilleries that adopt PA practices and of those that do not. Over 50% of the companies had adopted some of these practices. Overall, the data analysis suggests that these companies tend to have better results compared to those that do not adopt them. As shown in Table 1, the average sugarcane production of companies that adopt PA practices is about twice as large as that of companies that do not adopt them. Likewise, the average area is 1.6 times larger and the average for workers involved in agricultural activities is 1.5 times higher.

The data shown in Table 2 give information on the origin of the companies' capital and on the exporting orientation of the plants or distilleries. Among both categories of companies, namely for those that do and do not adopt PA, domestic-capital companies prevail. This is a coherent result, considering that the sugar and ethanol industry is still mostly dominated by Brazilian corporations. However, foreign companies will tend to increase gradually over the next few years because of the attractive production costs of Brazilian sugar and, in particular, because ethanol is seen as a feasible alternative for liquid fossil fuels in the short and medium term. Table 2 shows that of the 79 domestic companies, 58% adopt a PA practice, whereas among the eight foreign-capital companies 38% adopt it.

Table 2 shows that 66% of the 67 companies that export their products adopt PA practices. The greater adoption of PA practices by companies that export was to be

Table 1 Average features of sugar and ethanol companies that do or do not adopt PA for São Paulo state in 2008

Features	Adopt PA (1)		Don't adopt PA (2)		*p*-value*	Rate Col (1)/Col(2)
	Mean	Std. Err.	Mean	Std. Err.		
Production[a] (t)	2 136 475	228 925	1 196 842	172 445	0.003	1.79
Area[b] (ha)	22 103	2067.1	13 739	2569.3	0.012	1.61
Occupied staff[c]	1570	154.1	1034	120.9	0.005	1.52
Number of companies (%)	49 (56%)		38 (44%)			1.29

[a] Total amount of sugarcane crushed in the 2007–2008 harvest

[b] Total area (owned by the company and leased) planted with sugarcane

[c] Number of people employed in the company's agricultural activities

* The features showed significant differences (using *t*-test) between (1) and (2)

Table 2 Number of sugar and ethanol companies that do or do not adopt PA, according to their controlling equity and exporting orientation for São Paulo state in 2008

Companies	Origin of the company's controlling equity[a] (p-value = 0.289)*		Exporting orientation (p-value = 0.002)*	
	National	Foreign[b]	Exporter	Non-exporter
Adopt PA	46 (58%)	3 (38%)	44 (66%)	5 (25%)
Do not adopt PA	33 (42%)	5 (63%)	23 (34%)	15 (75%)
Total	79 (100%)	8 (100%)	67 (100%)	20 (100%)

[a] Controlling equity is national when it is directly or indirectly held by persons or corporations residing and domiciled in Brazil. Controlling equity is foreign when it is directly or indirectly held by persons or corporations domiciled abroad

[b] National and foreign capital (blended) companies are also included in this category

* The percentage differences were calculated using the Fisher's exact test. The origin of the company's controlling equity showed no significant differences between adopters and non-adopters. The exporting orientation differed significantly (p-value = 0.002)

Table 3 Number of sugar and ethanol companies that do or do not adopt PA, by group or unit and type of management for São Paulo state in 2008

Companies	Group or unit (p-value < 0.0001)*		Type of management (p-value < 0.0001)*	
	Group	Independent	Professionally managed	Family-run
Adopt PA	40 (80%)	9 (24%)	37 (76%)	12 (32%)
Do not adopt PA	10 (20%)	28 (76%)	12 (24%)	26 (68%)
Total	50 (100%)	37 (100%)	49 (100%)	38 (100%)

* Adopters' and non-adopters' responses that are significantly different (p-value < 0.0001) with a Fisher's exact test

Table 4 Financing sources (median) used by the plants and distilleries for São Paulo state in 2008

Companies	Financing sources (%)			
	Of their own (p-value = 0.002)*	Third-party		
		Total	Private (p-value = 0.043)*	Public (p-value = 0.022)*
That adopt PA (1)	100	0	0	0
That do not adopt PA (2)	62.5	37.5	10	20

* The financing sources (median) differed significantly (using the Wilcoxon test) between (1) and (2)

expected because exposure to international competition encourages them to invest in new technologies to meet a more demanding market and face the intense competitive pressures prevailing in the international market.

The results of whether companies belonged to a corporate group or were independent, and whether they were professionally managed or family-run are interesting. Table 3 shows that among the 50 companies that claimed to be part of a corporate group, 80% adopt PA technologies, whereas among the 37 that reported that they were independent

companies, only 24% adopt them. This result suggests the existence of group synergies, such as common use of PA equipment and information exchange. Another interesting result is that 76% of the 49 companies that reported they are professionally managed adopt PA technologies, whereas only 32% of the 38 that reported they are family-run adopt them. Therefore, Table 3 shows that companies that adopt these technologies are mainly professionally managed and belong to a corporate group.

The companies also reported their financing structure for plant and distillery expenditure. Table 4 shows that a company's own resources seem to be relatively more important than other financing sources, regardless of whether the company adopts PA technologies or not. The results also show that companies that adopt PA technologies have a larger percentage of resources of their own.

The capital opportunity cost, which can be defined as the profitability that capital may have as a result of its alternative use (if it were not invested in machinery and equipment for implementing PA practices), must be taken into account. This means that a plant or distillery could invest in the financial markets, considering investments in the same risk class, instead of investing in capital goods for PA.

Figure 3 summarizes the results of the rate of adoption for different PA technologies. Satellite imagery has one of the highest adoption rates, of 76%. Satellite images such as

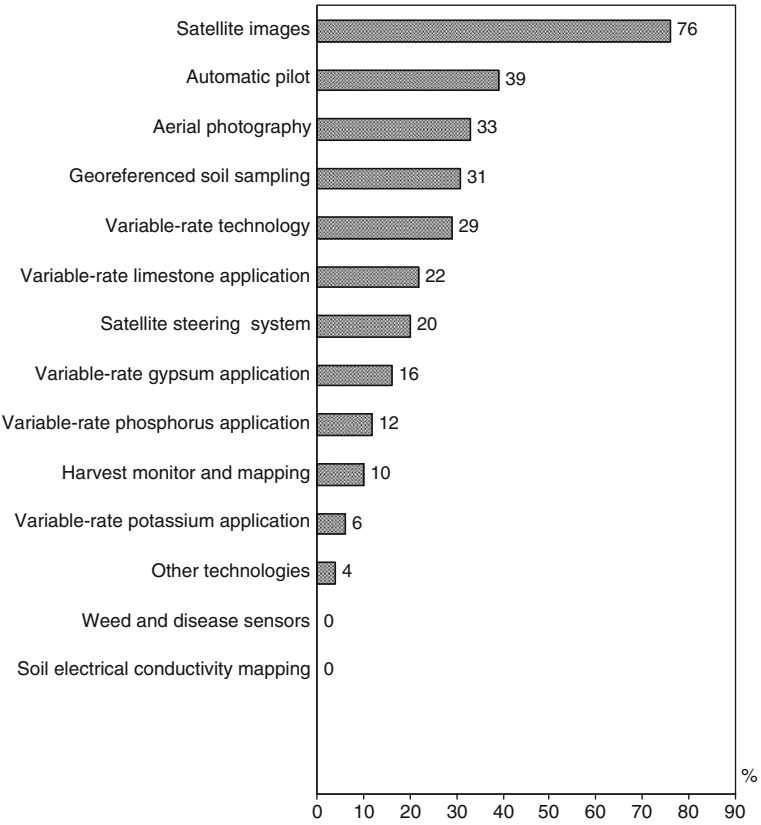

Fig. 3 PA adoption rate in sugarcane plantations according to different technologies for São Paulo state in 2008

aerial photographs, which have an adoption rate of 33%, may not be directly related to PA practices, but were listed as such by the executives of the companies. Among other techniques that deserve special mention in terms of adoption rate are automatic pilot (39%), georeferenced soil sampling (31%) and use of fertilizers and soil ameliorants (lime) at a variable-rate (29%). An automatic pilot is mainly used on tractors opening furrows for planting sugarcane. Some plants and distilleries are already using it on harvesters and also on tractors that follow the harvesters in internal transport operations for traffic control. Both georeferenced soil sampling and the use of inputs at a variable-rate are still exclusively associated with preparing the soil for replanting, which is done only once every 5 years on average on the same plantation. These practices are not yet being adopted for annual cultivation cycles in the post-harvest period.

Sensors and soil electrical conductivity mapping have not been adopted by any plants and distilleries that responded so far. As for other technologies, 4% of all plants and distilleries have adopted technology for spraying pesticides at a variable rate which, as opposed to the localized application of fertilizers and soil ameliorants (lime and gypsum), is still under development.

The data show that the average time that PA has been used in the plants and distilleries is 4 years. This result supports evidence that, although this technology is being adopted, it is still relatively recent in the country. However, Table 5 shows that over 80% of all plants and distilleries reported that they have three or more years of experience in using PA.

When the companies were asked whether they had plans to expand, maintain or reduce the use of PA practices, 96% of those that had adopted them reported an interest in increasing their use. Only 4% of the companies reported that they intend to keep using them at current levels and no plant or distillery reported an interest in reducing their use (Fig. 4). These results confirm the optimism of plants and distilleries for PA, leading us to believe it will become a major tool in future not only in the sugar and ethanol industry, but also in Brazilian agricultural companies at large.

Table 5 Percentage of companies that adopt PA, according to years of experience with the techniques for São Paulo state in 2008

Years	Percentage of companies
1–2 years	17
3–4 years	31
More than 4 years	52

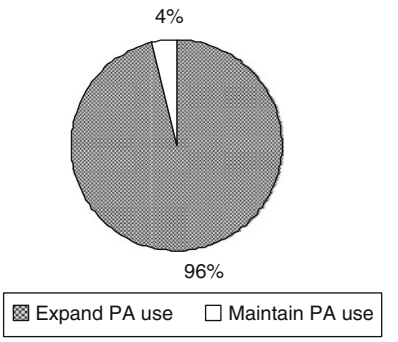

Fig. 4 Perception of PA use in the sugar and ethanol industry for São Paulo state—in 2008

Figure 5 shows the number of companies that hire PA services provided by third parties, either fully or partially. The data show that about 65% of the companies that adopt PA reported that they hire an outsourced service of this kind.

For these same companies, image acquisition (satellite images and aerial photographs) were the most frequently hired outside services (69%) (Fig. 6). Among other outsourced services hired by plants or distilleries, variable-rate agricultural input machinery (13%), automatic pilot equipment (9%) and georeferenced soil sampling (6%) stand out. These percentages are small suggesting that the services available have not been adapted well to the sugar and ethanol industry as yet. In addition, the high costs of these services rank third among obstacles that companies face in adopting PA.

The sources of information for implementing PA practices are a useful indicator for understanding the behavior of plants and distilleries; a project aimed at the adoption of PA can originate in the companies themselves or in an external source. Table 6 shows the percentage of companies that attached high and medium importance to the sources of information for adopting PA practices; suppliers of PA technologies (92%) rank first, followed by universities and research institutes (83%), specialized conferences, meetings and publications (77%), and consultancy firms and independent consultants (75%). In general, the data analysis suggests that the adoption of PA technologies in the sugar and ethanol industry results from the use of information acquired in commercial relations with suppliers, from educational and research centers, and from conferences and meetings.

The outcomes of PA in terms of the performance of plants and distilleries can be different; they can be profitable in certain, but not in all situations. Table 7 shows the frequency with which the impacts of PA practices investigated in this research were described by companies as of high or medium importance. For companies that adopt them,

Fig. 5 Companies that hire PA services provided by third parties or not for São Paulo state in 2008

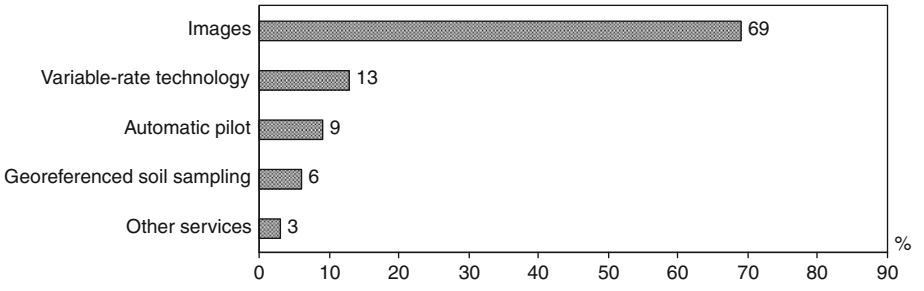

Fig. 6 PA services provided by third parties in the sugar and ethanol industry by type of technology for São Paulo state in 2008

Table 6 Information sources for adopting PA: percentage of companies that adopt it and that attached high or medium importance to specific information sources for São Paulo state in 2008

Plants and distilleries that adopt PA	
Information sources used	Percentage of companies
Domestic sources	
R&D department	71
Other units	51
External sources	
Another company of the group	16
Machine, equipment, component or software vendors	92
Competitors	61
Consultancy firms and independent consultants	75
Universities and research institutes	83
Specialized conferences, meetings and publications	77
Fairs and exhibitions	69

significant changes in management are the impact that was mentioned most (94%), followed by yield (78%), less environmental impact (73%) and reduced production costs (71%). These results are supported by the fact that PA is a management system designed to optimize production and minimize environmental impact.

The reasons why plants and distilleries do not adopt PA technologies, or the obstacles that prevent them from implementing them, provide valuable information for defining and evaluating public policies designed to foster the use of new technologies in the sugar and ethanol industry. Figure 7 shows that companies that adopt PA technologies attached high or medium importance to them in each problem category, and their high cost (96%) is the obstacle that was most frequently mentioned, followed by the lack of skilled staff (94%) and the high costs of services (88%). Of particular relevance in Fig. 7 is that 82% of the plants and distilleries that adopt these technologies attached high or medium importance to a lack of information about them. In addition to the problems and obstacles listed in the

Table 7 Precision agriculture impacts: percentage of companies that adopt it and that attached high or medium importance to specific impacts for São Paulo state in 2008

Plants and distilleries that adopt PA	
Impact caused	Percentage of companies
Significant management changes	94
Improvements in sugarcane quality	67
Higher yield	78
Lower production costs	71
Lower environmental impacts	73
Higher market share for the company	59
Compliance with regulations related to the domestic market	63
Compliance with regulations related to the international market	57

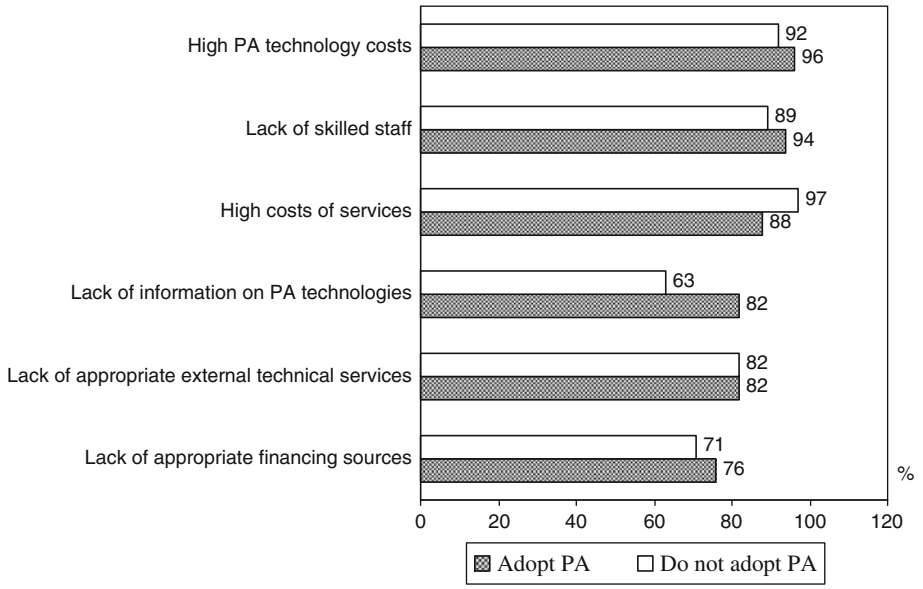

Fig. 7 Problems and obstacles indicated by plants and distilleries that adopt PA or not for São Paulo state in 2008

questionnaire, some plants and distilleries reported other factors that jeopardize the adoption of PA practices, such as lack of experience of suppliers that sell PA-related equipment and who do not know how to use it correctly, poor adaptation for the sugarcane plantations, and the lack of appropriate and economically feasible technologies.

Among other problems mentioned by companies that do not adopt PA technologies, the high costs of services (97%) rank first, followed by the high costs of the technologies (92%) and lack of skilled staff (89%), as observed for plants and distilleries that do adopt them. Other problems were mentioned by plants and distilleries that do not adopt PA technologies. These include operational difficulties (many tools have been designed for large areas), lack of specialized professionals, long periods of time before seeing a return on investments, lack of dissemination and knowledge of their benefits, and resistance to change within the companies.

Regardless of whether the plants and distilleries adopted PA technologies or not, economic factors were the main obstacles to their adoption. Among them, high costs were considered to be the main one. One of the main challenges for fully adopting these technologies is to reduce machinery and equipment acquisition costs. Apart from low-cost equipment, the adoption of these technologies on a large scale depends on simpler and more efficient technologies, increased perception of profitability as a result of using them and training of skilled labor (Mattoso and Garcia 2006). Equipment designed specifically for sugarcane would also contribute to the greater adoption of PA.

Conclusions

The main conclusions of this research suggest that the results for plants and distilleries that have adopted and used PA technologies are positive, such as managerial improvements,

higher yield, lower costs, minimization of environmental impacts and improvements in sugarcane quality.

There is no doubt that adopting and using technologies that are less aggressive to the environment and designed to improve soil productivity and profitability, which are being increasingly appreciated, will become an indispensable tool for Brazilian agribusiness companies in the coming years. As PA begins to be adopted on a large scale, the analyses of its adoption and use will provide relevant information for designing public policies to stimulate and support its use.

As for public policy tools designed to disseminate these technologies to a larger audience, reducing interest rates and enhancing access to credit are the best ways to make sure that this objective is achieved. However, as seen in this paper, companies operating in the sugar and ethanol industry consider difficulties of accessing credit to be a major obstacle preventing the adoption of new technologies. This seems to indicate these companies' perception of the need to have financial resources available at a low cost to stimulate the adoption of PA in Brazil.

It is expected that the results reported in this paper will provide positive inputs to Brazilian plants and distilleries by making them more aware of the importance of tools to reduce costs, minimize environmental impacts and enhance the competitiveness of the Brazilian agri-industry as a result. Finally, the study in this paper refers to the sugar–ethanol industry in São Paulo state only, and for this reason surveys in other regions where PA technology is being adopted should be done to ensure the results are relevant nationally, even if they are not intended to lead to conclusions or generalizations. In this sense, we hope that this study will be used to stimulate a variety of more comprehensive activities leading to a solid understanding of PA use and adoption in Brazil.

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