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"Too Early or Too Late? Assessing The Adoption Level of Precision Agriculture in Brazil"

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TOO EARLY OR TOO LATE? ASSESSING THE ADOPTION LEVEL OF PRECISION AGRICULTURE IN BRAZIL

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Abstract

The adoption of Precision Agriculture (PA) is discussed in this article, focusing on Brazilian economy, one of the economies with the greatest potential for its adoption. The adoption of innovative practices entails different perceptions from the various communities involved – from researchers, innovators, to farmers. Thus, this paper discusses the different perception of these groups of economic agents in contact with the Brazilian PA. It also compares the results obtained with previous works focused on this reality. It was possible to verify that different groups have a different perception of PA adoption, which is situated, in the central estimate, at *early majority* level for diagnostic tools and *innovators* for application tools. Such results suggest the need of an effective management of PA adoption in Brazil, and probably in other emerging economies, at the risk of the advantages perceived by the groups more familiar with technological development being not the same as most other communities of adopters.

Keywords: technological adoption, diffusion of innovation, digital technologies in agriculture, adoption lifecycle, agricultural machinery and equipment

Statements and declarations

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INTRODUCTION

Precision agriculture (PA) is a technological and managerial dual system resulting from a convergence between information and communication technologies (ICT), agricultural machinery, and site-specific field management. Cognitively, PA values farmers' prior intuitive knowledge of the spatial variability of the field to support agronomic decisions, but now in a data-intensive and codified way. PA adoption provides a different level of agricultural production, opposed to massification trends (Gutman & Robert, 2013, p. 166), with the additional potential to mitigate the environmental effects of agricultural activities.

The trend towards PA has been increasing around the globe. However, like any process of adopting new technologies, the adoption of PA faces several stages that can be described by models of innovation diffusion. Brazil has a significant market share of agricultural production on a global scale. Given its size, Brazil is the third largest food exporter in the world. According to forecasts from the Ministry of Agriculture, Livestock and Supply, Brazilian agricultural production is expected to increase from 232.6 million tons in the 2017/18 crop to 302 million by 2027/28, representing an increase of 69 million tons (2.5% growth per year). The Brazilian area for grain production will have 63 million hectares in the 2018/19 harvest and is expected to expand to 71 million by the 2027/28 harvest. This growth was based on the 70% increase in grain production in the country in the last ten years.

Given the dimensions of the Brazilian case, it is important to observe how precision agriculture (PA) has been established in this country. Molin (2014, p. 7) recognized a significant potential demand for PA in Brazil, as there is an active market with a growing number of companies. However, reliable statistical data on that topic are scarce.

In the case of Brazil, few studies have focused on this issue. The intention of this paper is to fill this gap. Therefore, this work evaluates the perception of a sample of experts in the agricultural field regarding the stage of PA already spread across Brazilian territory. Information available in this paper is complemented with interviews performed with market and technical leaders involved in PA development in Brazil.

The remaining sections are as follows: *Theoretical Background and Context* introduces the theoretical background and the Brazilian context for PA. *Methodological Steps for Assessing the Adoption of PA in Brazil* describes the following methodological steps and the achieved results for testing the hypotheses concerning whether the variances obtained from respondents' replies are the same or close to the previous replies published

in the few studies about PA adoption in Brazil. *Results and discussion* and *Conclusion* raise significant implications and challenges.

THEORETICAL BACKGROUND AND CONTEXT

Technological adoption and precision agriculture

Technology adoption modeling begins in agriculture with Griliches' (1957) seminal work about a variety of hybrid maize. He established the first measure of agricultural technological adoption: the property area covered by a given innovation (p. 506), having discussed the so-called S curve (Figure 1A), which is still quite influential (Vieira Filho & Silveira, 2012, p. 726, footnote 8). Hybrid maize had different adoption rates in different U.S. states, as it was the result of heterogeneous attempts to adapt to local/state conditions (Griliches, 1957, p. 506). Based on this, Rogers (2003) developed his model of innovation diffusion, which classifies adopters into five groups: innovators, early adopters, early majority, late majority, and laggards (Figure 1B).

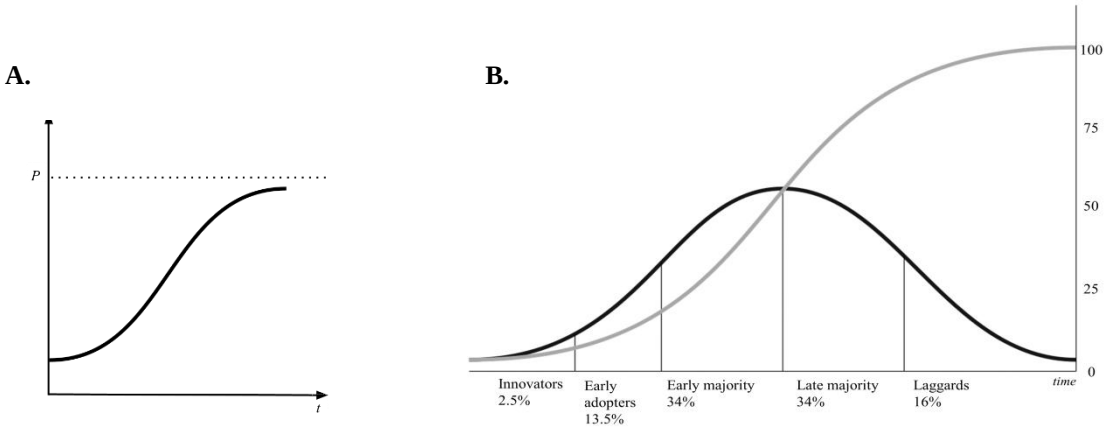


Figure 1. A. Griliches' S curve. **B.** Diffusion of innovation curve.

Sources: **A.** adapted from Griliches (1957). **B.** Rogers, E. M. (2003, p. 5.869).

Note. **A.** $P = K/(1 + e^{-(a+bt)})$, "where *P* is the percentage planted, *K* is the ceiling or equilibrium value, *t* is the time variable, *b* is the rate-of-growth coefficient, and *a* is the constant of integration which positions the curve on the time scale" (Griliches, 1957, p. 504).

According to Figures 1A and 1B, there is a progressive assimilation of the new technological processes (such as PA) over time. Starting with small fringes of innovators (see Rogers, 2003, which quantifies

approximately 3%), it is assumed that the technological processes accumulate more significant percentages of adopters, tending to a level at which the entire population assimilates innovation in a given, but long period of time.

However, works such as those of Rosenberg (1976) contest this linear approach, alleging that a technological process has hardly reached the population in its maturity because other concurrent technological processes have entered the scene, competing for adoption by that same population. This alternative view has been called the “evolutionary perspective”. In general, this perspective contrasts with the neoclassical approach represented by Griliches and Rogers, which focuses on costs and disregards influences from social context. For Rosenberg (1976), the interaction between competition and complementarity asks for no more of an analysis of each innovation alone except for what the author calls "innovation clusters" (p. 67), based upon what Schumpeter (1935, p. 6) stated about the change of direction from existing innovations. In a similar vein, Freeman and Pérez (1988, p. 45-47), in their taxonomy of identification patterns of innovation in the process of generation and adoption of technologies, define *new technological systems* as a constellation of radical and incremental innovations related both technically and economically.

This systemic approach to technological adoption is proposed specifically for the evolution of agricultural systems and their appropriation of ICT (Rodrigues, 2013, p. 25), aiming to explain the evolution of ICT-based technologies through complex relationships between the various actors operating in the agricultural system, their learning processes, and the evolution of institutions. Such an approach seems best suited for analyzing the diversity of situations in developing countries, where more advanced ICT-based products and services tend to be restricted to a few dynamic clusters.

Considering precision agriculture (PA) as a modular concept (Silva, Pamplona, & Penha, 2020), it is referred to as a technological (ICT-based) and managerial system for agriculture that provides optimization of resources with concurrent gains in sustainability, allowing to take advantage of spatial, temporal, and cultural variability. Its adoption somewhat follows the order of these functional categories (Inamasu & Bernardi, 2011, p. 23 and 29; McBride & Daberkow, 2003, p. 24):

1. Diagnosis (or reading): methods of data collection and analysis of spatial variability of several variables
2. Application (or performance): implementation of site-specific input application decisions using computer-controlled devices
3. Management (or interpretation and planning): usage of information generated by previous categories to improve economic and agronomic decision-making processes

Table 1 was conceived as a non-exhaustive attempt to organize PA *clusters of innovations* or *technological systems* considering those functional categories.

Table 1

Precision Agriculture – Major Products and Services by Functional Category

Diagnostic	Application	Management
GPS/GIS satellite systems and imaging	Autopilot: satellite- or map-driven	(Near) real-time transmission software and data integration
Sampling and mapping of electrical conductivity, soil composition, yield, harvest, etc.	Variable rate machines and implements, irrigation, planting, harvesting, and animal feeding	Decision-support and prescription software for agronomic practices in specific pieces of land
Planting, productivity, harvest, and animal monitors	Selective pest control	Site-specific or satellite-driven corrections and prescriptions
Soil attribute and plant sensors	UAV, drones	Telemetry remote sensing: temperature, humidity, and dripping
UAV, drones		

Note. GPS: global positioning system; GIS: geographic information system; UAV: unmanned aerial vehicles. Source: technologies extracted from Scaramuzza et al. (2016, p. 17), European Innovation Partnership, Agricultural Productivity and Sustainability (2015, p. 4)

However, a given process can also be perceived differently by different samples of adopters. This problem has been discussed in depth by authors as Chian (2010) and Andersson et al. (2011), summarized in Figure 1C. Although several agents may be involved in the same adoption phase, differences in region, age, gender, educational qualifications, and access to information or differentiated valuation of costs and benefits may justify this difference in perception. The difference in the perception of the adoption stage is very important in the management of adoption processes for three main reasons. First, if there are agents having large gaps not only in the perception of gains but also in the costs of innovation processes, it has been suggested that this heterogeneity generates biased signals for investors and public managers, leading to biased decisions. Second, comparing different studies, the difference in perception can also indicate an evolution in the adoption process; thus, for

example, if sample B (in Figure 1C) was collected earlier than sample A, then new phases of the adoption process may be faced, marked by the low probability of B's responses coinciding with those of A (through F tests, for example). Finally, the difference in perceptions of adoption may also show a difficulty present in certain social groups or in economic communities in perceiving the gains of the innovation process in question, signaling the need for better work on behalf of the communities.

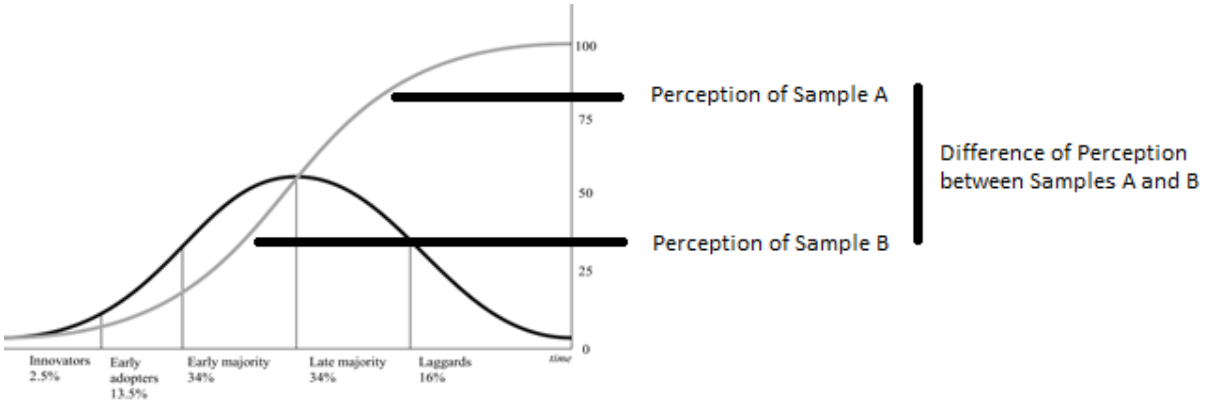


Figure 1. C. Difference in perception of the adoption stage between samples.

Studies that measure precision agriculture adoption in Brazil

Table 2 shows the six studies already published on precision agriculture (PA) adoption in Brazil, using surveys and quantitative approaches to measure some aspect of PA adoption. The PA adoption level among grain farmers in certain regions – the southwest of Goiás (Soares Filho & Cunha, 2015) – was identified as low, but PA adoption has been found to be relatively high in other areas (southwest of São Paulo – Leite, Castro, Jabbour, Batalha, & Govindan, 2014), as well as relatively high for sugarcane plants and distilleries in São Paulo (Silva, Moraes, & Molin, 2011). In the most comprehensive study, crops are cultivated on farms that adopt PA at a certain level, but this does not necessarily happen for each crop, as the average percentage area that adopts PA is 65.4% (Bernardi & Inamasu, 2014, p. 569).

Table 2

Crops mentioned in articles that measure precision agriculture adoption level in Brazil

Articles	Period of	N. of	Crops mentioned	Quantitative evaluation of PA

	application	respon-dents		adoption
Pinto, Ferreira, & Teixeira (2017)[a]	1st sem./2016	105	Soybean	--
Borghi et al. (2016)	Harvest 2011-2012	25	Soybean, maize, cotton, pasture, beans, sugarcane, wheat, and coffee	All of them adopt precision agriculture
Soares Filho and Cunha (2015)	Jul./2012 to Jul./2013	43	Grains	6.67% of the total area under PA (1,500,000 ha; grains, southwest of Goiás)
Bernardi and Inamasu (2014)	Sept. and Nov./ 2012	301	Soybean, wheat, beans, sugarcane, sugar, sorghum, cotton, beef and dairy cattle, rice, coffee, millet, fruits, arroz, café, oats, barley and sunflower, vegetables, and ornamental plants[b]	53.16% of respondents adopt PA, with areas 140% larger than nonadopters on average (diverse crops in 9 Brazilian states)
Leite et al. (2014)	2nd sem./ 2013	53	Grains	49% with some level of PA implementation and 30% with considerable or complete implementation (grains, southwest of São Paulo)
Silva, Moraes, and Molin (2011)	2nd sem./ 2008	87	Sugarcane	56% of companies adopt PA, whose area is 60% higher on

		average and production almost 80% higher than that of nonadopters (sugarcane, São Paulo state)

Note. Source: Prepared by the authors. [a]This is a study on determinants to precision agriculture (PA) adoption, so the data do not allow differentiation between adopters and nonadopters. [b]These crops are cultivated in the farms of the sample, but the research study does not indicate which of them truly use PA.

Table 3 presents the technologies mentioned in these same studies. In these works, soil sampling and variable-rate technologies have the highest frequencies. Guidance technologies have been identified as emerging technologies, especially autopilots. It is also worth mentioning that the only technology within the management category is telemetry.

Table 3

Tools mentioned in articles that evaluate the adoption level of precision agriculture in Brazil

Articles	Diagnosis	Application	Management
Pinto, Ferreira, & Teixeira (2017)[a]	Grid soil sampling, productivity maps, remote sensing	Variable rate application technologies, light bar	
Borghi et al. (2016)	Grid soil sampling, GIS crop maps, satellite/aerial imagery, soil electrical conductivity mapping, ground sensors for mapping, on-the-go sensors	GPS guidance w/manual control/lightbar, GPS Guidance w/auto control/auto steering, GPS to manage vehicle, machine, and implement logistics	Telemetry
Soares Filho e Cunha (2015)	Grid soil sampling, crop monitoring and mapping, satellite imagery, aerial photography, electrical conductivity mapping	Variable rate application technologies, autopilot, lightbar guidance system, precision sowing, precision irrigation	
Bernardi and Inamasu (2014)	Soil analysis, mapping or aerial imagery for property management,	Variable rate seeder/fertilizer, lightbar, variable rate	

	harvester w/harvest sensor	fertilizer/limestone spreader, autopilot
Silva, Moraes and Molin (2011)	Satellite imagery, aerial photography, georeferenced soil sampling, crop monitoring and mapping, other technologies	Autopilot, variable rate technologies, variable rate fertilizer/corrective application (limestone, plaster, phosphorus, potassium), satellite-driven steering system

Notes. GIS: geographic information system; GPS: global positioning system. Source: prepared by the authors. [a]Technologies that constitute most of the practices adopted in Brazil (Molin, Amaral, & Colaço, 2015, cited by Pinto, Ferreira, & Teixeira, 2017).

Thus, from the literature on the topic, this study intends to assess whether the respondents contacted are in line with respondents from previous studies on PA in Brazil. If the respondents are not aligned, the analysis demonstrates whether there was an evolution in the PA phase reached in Brazil or if the differences in perception are due to sampling issues. The next section demonstrates the methodological efforts in this regard.

METHODOLOGICAL STEPS FOR ASSESSING THE ADOPTION OF PA IN BRAZIL

Based upon previous works, Tables 2A and 3A (Appendices A and B) were built, in which the referenced studies show a considerable disparity in the distribution of responses, typical of works in meta-analysis. These tables show that, throughout the cited works, there has been an evolution in certain *application tools*:

- GPS guidance with auto-control/auto-steer increased from 39% identified by Silva et al. (2011) to 56% by Borghi et al. (2016);
- Guidance systems with manual control/lightbars increased from 22.21% by Bernardi and Inamasu (2014) to 89% by Borghi et al. (2016);
- Variable rate technologies, increasing from 29% by Silva et al. (2011) to 89% by Borghi et al. (2016).

The evolution of *diagnostic tools* was even more expressive in two cases:

- Grid soil sampling increased from 97 to 100% according to Borghi et al. (2016);
- Harvest/yield monitoring (using GIS or not) increased from 10% by Silva et al. (2011) to 56% by Borghi et al. (2016).

In this systematic review of the literature, some *diagnostic tools* revealed divergent results (namely, aerial mapping or imagery). Despite this situation, most of *diagnostic tools*, as well as most of *application tools*, allow

to suggest that these technical elements of PA are in advanced stages of adoption (given that more than 50% of adopters have recognized the adoption of certain tools).

However, as pointed out previously, most of these works focused on a respondent population linked to agricultural work. Additionally, as demonstrated in the Appendix, there was a significant level of heterogeneity among these results. As Gephart (2018, p. 34-5) and Bardin (1977) point out, sampling techniques focused on certain professional groups can also lead to a high probability of obtaining biased survey results. Instead, the use of interviews directed to specialists has several methodological advantages:

- a reduction in costs for conducting interviews and collecting data;
- a greater depth of content derived from the variety of responses and perceptions on the part of the interviewees;
- obtaining more objective knowledge without losing the variability of responses;
- obtaining the most up-to-date results on a given phenomenon.

Designing interviews with experts on the adoption of precision agriculture in Brazil

As a preliminary step, a meta-analysis exercise was run considering all works published about PA adoption in Brazil. This step is commented as an Appendix section. The meta-analysis exercise developed on the data collected from the published studies showed significant heterogeneity in the surveys on the perception of the adoption of the *diagnostic* and *application tools* of PA (see related Appendix section). As such, there is a set of steps to be observed in the remaining discussion:

- using complementary analysis methods, namely, interviews with specialists;
- conducting F tests to understand the proximity of the responses obtained to the responses provided in each study;
- In the case that the F tests reject the null hypothesis of proximity of the answers, proposing a set of values as well as respective confidence intervals for the estimates of the parameters associated with the phenomenon;
- And, finally, preparing an integrated comment on the various results.

Thus, the method proposed by Gephart (2018, p. 34-5) was followed, supported by the five criteria that favor the selective interview technique (Bardin, 1977):

1. the need to avoid skewed readings due to the respondents' professional concentrations;
2. the need to achieve consistent results while avoiding unnecessary costs;
3. the duty to choose a group sufficiently representative of the diversity of opinions;
4. the ability to guarantee the interviewees' consent and the seriousness of their answers to the question;
5. robust suggestions from the literature (Bardin, 1977; Gephart, 2018).

Additionally, Taherdoost (2016) or Etikan, Musam and Alkassim (2015) suggest the opportunity to use certain meetings (such as congresses or business fairs) for the moment of collecting responses. Such meetings tend to enable a representative sample of the target universe. Additionally, these meetings, being concentrated at a given time, tend to allow an expressive statement of the experts' opinions in relation to the identified time (Taherdoost, 2016). In the Brazilian case, the largest meeting of specialists in PA is the “Brazilian Precision Agriculture Congress”. Thus, the collection of interviews for this work was performed at the 2018 meeting of this Congress. In accordance with the previous highlighted five criteria, interviews were conducted with 10 experts in the field of PA.

Regarding the interview model, an option for open-question forms was made. In open interviews, “viewpoints are more likely to be expressed in an openly designed interview situation than in a standardized interview or a questionnaire”, which is strengthened with a responsive style that aims “to develop a fuller picture of interviewees’ points of view, rather than just simple, short, general, or abstract answers to the interviewer’s questions” (Flick, 2014, p. 265). As guiding questions, the following two were stipulated:

- “How do you rate the level of PA adoption in Brazil? Can you consider a simple rate like “Low, medium or high?”;
- Which crops and technologies do you consider that are more advanced in this adoption?”.

In addition, purposeful sampling selects people or events that are intentionally chosen because they provide important information that cannot be obtained otherwise (Taherdoost, 2016). Specialists and their respective professional classes were also purposefully chosen. Specialists were chosen considering the two groups:

- *Education and research:* These have the function of validating technologies, qualifying people, and reflecting on macro processes, including agricultural research institutes, universities and technical schools.
- *Market:* These focused on their customers’ behavior, as well as on the whole market, such as machinery and implement manufacturers, and consulting and service providers.

Ten interviews were then conducted and recorded, with the specialists profiled in Table 4.

Table 4

List of respondents (interviews conducted during the Brazilian Precision Agriculture Congress 2018)

Interview date	Professional class	Agent sector	Agent level	Respondent position	Code
Oct. 2nd	Education and research	Universities and technical schools	State	Associate professor	1A
Oct. 2nd	Market	Machinery and implement	National	Product marketing coordinator	1 M
Oct. 2nd	Market	Consulting and service providers	National	Director	1CS
Oct. 2nd	Market	Consulting and service providers	Multinational	Sales regional coordinator	2CS
Oct. 2nd	Market	Machinery and implement	National	Project manager	2M
Oct. 3rd	Education and research	Agricultural research institute	National	Researcher	1I
Oct. 3rd	Education and research	Agricultural research institute	State	Researcher	2I
Oct. 3rd	Education and research	Universities and technical schools	State	Full professor	2A
Oct. 3rd	Education and research	Universities and technical schools	State	Professor	3A
Oct. 3rd	Market	Consulting and service providers	National	Product manager	3CS

Note. Source: prepared by the authors. PA: precision agriculture. All interviews were conducted with a cell phone recorder during ConBAP 2018, without previous contact with the agents. To ensure their freedom to

express opinions, respondent names and their respective organizations were not disclosed. Interviews are available to other researchers if they sign a nondisclosure agreement and assure that there is no risk of jeopardizing the privacy of respondents regarding compliance rules of their institutions and companies.

The next section presents the results and the respective discussion, starting with the respondents' replies considering differences in crops and in functional categories, and followed by the quantitative analysis comparing these replies with the results of articles in Table 2.

RESULTS AND DISCUSSION

Precision agriculture adoption by crop

Respondents highlighted certain crops (such as soybean, sugarcane, cotton, or maize) as the most advanced in the adoption of precision agriculture (PA). This is explained by Brazilian leadership in the production of these three crops, with larger cultivation areas and mainly higher investments, which confirm these crops as main PA adopters (Nova Cana, 2018; Brazilian Cotton Growers Association, 2016). Table 5 presents the respondents' evaluations by crop.

Table 5

Crops in Brazil and Precision Agriculture Adoption Level According to Respondents

Crops	Respondents that mention specific crops	
	Significant level	**Low, initial, potential, or uncertain level**
Soybean	1I, 2I, 3A, 1CS, 2CS, 3CS, 2M	-
Maize	1CS, 2CS, 2M	-
Sugar cane	2I, 1A, 3A, 1M, 2M	-
Cotton	1I, 2I, 1A, 1CS, 2CS, 2M	3A
Grains	2I, 1A, 2A	-

Cereals	1M	-
Coffee	1CS, 3CS	2I, 3A
Citrus	1CS, 3CS	2I
Fruit	3A	3A, 2M
Bean	2CS	-
Forestry	3A	2I
Greenhouse	3A	-
Cattle	-	2I
Pastures	-	2I, 2CS, 2M

Note. Source: Prepared by the authors.

Precision agriculture technologies adopted in Brazil by functional category

Table 6 contains respondents' replies regarding the adoption of *diagnostic* and *application tools* related to PA in Brazil.

Table 6

Adoption level of precision agriculture tools in Brazil according to the respondents

Tools	Mentions by respondents	
	Significant	**Low**
Diagnostic		
Geostatistics (generation of soil, productivity, and other maps)	2I	--
Sensing	2I	--
GPS	2I	--

Harvest monitoring	2A	--
Soil sampling	2A	--
Climatic station	3CS	--
Pest monitoring	3CS	--
Application		
Automatic pilot	2I, 2A, 3A, 1M, 2M	--
Section/flow controller	3A	--
Variable rate input application	2A, 1M	--
Management		
Artificial intelligence and systems	--	2I
Decision-making Technologies	--	3A

Note. Source: prepared by the authors. GPS = global positioning system. As the mentions were spontaneous, there is an overlap between tools and tool categories. Respondents 1I, 1A, 1CS, and 2CS did not mention any technology as the most adopted.

According to Table 6, mentions of diagnostic tools are sparse; however, autopilot stands out among the application tools, which likely indicates a higher level of adoption. Respondents 2I and 2A dispute their characterization as PA, as they are unrelated to spatial, temporal, and crop variability. However, they are mentioned by three of five members of the group of respondents from the sector "education and research". Additionally, these technologies have also been unanimously referred to by machinery and implement manufacturers.

Two management technologies are mentioned as having a low adoption level: systems and artificial intelligence (2I) and decision-making technologies (3A), consistent with the information found in the literature. Two other diagnostic technologies are also noteworthy, especially from respondent 1I's reply:

> *acabou de ser enfatizado aqui na palestra do professor americano [Ken Sudduth] e talvez agora vire moda no Brasil, porque precisa vir alguém de fora falar para a gente acreditar, é a condutividade elétrica [...]. [Os mapas de condutividade elétrica] já são uma realidade na Austrália de muito tempo, [...] você tinha o próprio produtor já colhendo, já usando o equipamento [...]. E a condutividade elétrica e a*

> *produtividade são mapas essenciais para você orientar o que eu chamo de AP, que é otimização da amostragem de solo e a geração de zonas de manejo.* [It has just been emphasized here in the lecture by the American professor [Ken Sudduth] and it may now catch on in Brazil, because someone needs to come from abroad and say something for us to believe, it is electrical conductivity [...]. [Electrical conductivity maps] have been a reality in Australia for a long time, [...] you had the producer himself already harvesting, already using the equipment [...]. Electrical conductivity and productivity are essential maps for you to guide what I call PA, which is the optimization of soil sampling and management zone generation.]

The trend of reducing the sample grid in the soil analysis was also mentioned as a problem by respondent 1I, a soil analysis expert. This respondent understands that some diagnostic tools are misused to characterize PA:

> *Você está fazendo um mapa de atributos de solo, uma grade amostral de 1 ha, que ninguém faz porque é muito cara, [...] agora se faz 2 ha, 3 ha. [...] Você tem uma distância de 100 m de uma amostra para an outra e está querendo caracterizar atributos de solos. Tem uma dependência espacial muitas vezes menor do que 100 m. Então como é que você vai enxergar uma variação menor do que 100 m se a tua amostragem é maior do que 100 m? Então você não está falando de fato de agricultura de precisão.* [You are mapping attributes of soil, a sample grid of 1 ha, which nobody makes because it is too expensive, [...] now it is made with 2 ha, 3 ha. [...] You have 100 m from one sample to another and you want to characterize soil attributes. Spatial dependence many times less than 100 m. So how are you going to see a variation of less than 100 m if your sample is larger than 100 m? So you are not truly talking about precision agriculture.]

Given that soil analysis is an essential tool at the diagnostic level, the distance between Brazil and the United States in soil sampling (respondent 1CS) is greater than it would seem at first glance, as well as the opportunity to expand this market if the sampling prices fall.

Evaluation of the level of precision agriculture adoption in Brazil

After the identification of crops with the most intensive use of PA tools, respondents' answers considering the level of PA adoption in Brazil were also analyzed. This analysis shows divergent perceptions about PA adoption levels in Brazil (see Appendix B for highlights of the responses). There is also a wide range of arguments to justify the perceived adoption level. Within the class of professional educators and researchers, most opinions

range around an intermediate level of PA. Respondent 1I understands that the PA technological system can have a high adoption level, while the managerial system has a low adoption level.

> *do meu conhecimento, eu estou fazendo uma estimativa de cabeça aqui, eu diria que 70% das máquinas colheitadeiras que têm sensor de produtividade, os sensores não são nem ligados*. [To my knowledge, I am making an estimation off the top of my head, I would say that 70% of the harvesters that have a productivity sensor, the sensors are not even turned on.]

Respondent 1A indicates a community of users of approximately 15 to 20% of farmers using PA kernel technologies. However, it is worth asking what these "PA kernel technologies" are about. His opinion is partially corroborated by 2A in regard to grain crops, but he agrees with 1I regarding the low adoption level of the managerial system. On the other hand, respondents 2I and 3A, explicitly using Roger's (2003) *diffusion of innovation model*, give slightly different evaluations: the former assures that Brazil would be in the middle of the adoption curve (converging with the observations in previous studies about PA in Brazil). Overall, these respondents suggest that a few PA technologies would have already reached at least 15% of Brazilian farmers.

Respondent 1CS explicitly admits this bias but classifies somewhat similarly to 1A; this respondent suggests a PA adoption level of 12 to 15% but with a trend of rapid growth. Respondent 2CS does not assess PA adoption level directly but observes a constant demand for services from his company (a large agribusiness consultancy firm) and attributes this in part to the generational change in farm management to be carried out by a newer generation with higher education and constant access to the internet. Finally, the evaluation of respondent 3CS seems contradictory, affirming a high level of adoption, but still considering the need to prove PA value among farmers, who have problems understanding their own needs and using data generated by diagnostic and application tools in farm management. It is plausible that this understanding is close to 1I and 3A, for whom diagnostic and application technologies are widespread, i.e., PA technological systems or infrastructure, and management tools are the next point to be reached.

The two respondents from the group "Machinery and implement manufacturers", in turn, agree with each other in their evaluation of a low PA adoption level in Brazil. Respondent 1M problematizes this assessment, from which two main issues are inferred: 1) the best possible indicator of PA adoption level, accepted by the agents involved, given the various products and services under this name and their different profiles; 2) the use of complete PA, that is, a technological system plus a managerial system. In addition, respondents 1 M and 2 M share concerns about barriers to small- and medium-sized farmers, as the latter do not see the value of PA as do the larger ones.

Now, the frequency of the responses obtained in the interviews about the adoption of the various *diagnostic* and *application tools* were compared with those of previously published works. For this purpose, two statistical tools were used: F-tests and correlation coefficients. These two statistical techniques have been extensively studied, so procedural details were not developed. It should be recalled, however, that the *p*-value of the F-test approximates the probability that two data matrices (in this case, the frequencies of responses versus the frequencies of the responses collected from each identified article) have similar variations. The correlation coefficient is a statistical measure of the joint variation of these two data sets. Table 7 presents the details of the analysis.

Table 7

Comparison between respondents' frequencies against previous precision agriculture studies

	On PA Diagnostic Tools		On PA Application Tools	
	F-test (*p*-val)	Correlation Coef.	F-test (*p*-val)	Correlation Coef.
Respondents × Pinto. Ferreira. & Teixeira (2017)[2]	0.0003	0.6173	0.0000	0.0372
Respondents × Borghi et al. (2016)	0.0040	-0.1109	0.0694	-0.3697
Respondents × Soares Filho & Cunha (2015)	0.0000	0.1124	0.0487	0.6698
Respondents × Bernardi & Inamasu (2014)	0.0000	-0.0575	0.2901	-0.0519
Respondents × Silva. Moraes. & Molin (2011)	0.0000	-0.3481	0.7995	-0.0969

On the one hand, Table 7 shows that respondents allowed the recognition of frequencies for the adoption of the *diagnostic tools*, which has a variation significantly different from the variation associated with each of the works confronted. Regarding PA *application tools*, the variation in frequencies identified in the interviews is significantly similar to those in the works of Silva et al. (2011) and Bernardi and Inamasu (2014). On the other hand, it is important to note that the higher correlation coefficients for the responses collected from interviewees are in line with the responses of Pinto et al. (2017) for *diagnostic tools* and Soares et al. (2015) for *application tool*s.

To finally assess the estimates for the most likely stage of adopting *diagnostic* and *application tools* in PA, the central estimates achieved by the systematic review of published works were compared with a meta-analysis conducted against the results of the interviews. Following authors such as Lavallée & Beaumont (2015) or Rao and Wu (1988), despite the *expertise* of the interviewees, several central estimation scenarios have to be presented – from only considering the respondents (in which the final assessment would result from 100% weighting for the interviewees and 0% for the values of other works) up to the 50-50 model (50% weighting for the interviewees and 50% for the values of other works) and up to the 60-40 scenario (60% weighting for the interviewees and 40% for the values of other works). Table 8 and Figures 2 and 3 summarize the estimates.

Table 8

Estimation of the relative frequency of Brazilian adopters of precision agriculture tools

Weights (Respondents–Other works)	**Diagnostic Tools**	**Application Tools**
100-0	22%	10%
60-40	31.6%	16%
50-50	34%	17.5%
Trending Phase	**Late Early Adopters**	**Initial Early Adopters**

Thus, following the results of Table 8 and Figures 2 and 3, the level of adoption of PA in Brazil is still in the phase of *early adopters*, observing that the use of *diagnostic tools* is at a more advanced stage than the adoption of *application tools*.

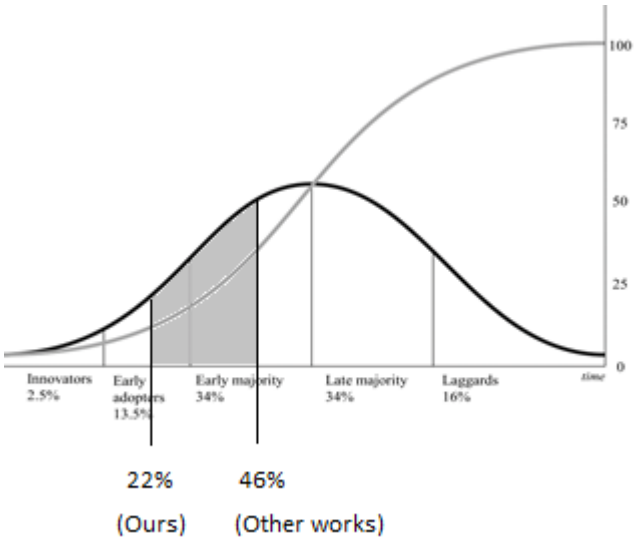


Figure 2. Estimation of the Relative Frequency of Brazilian adopters of PA diagnostic tools

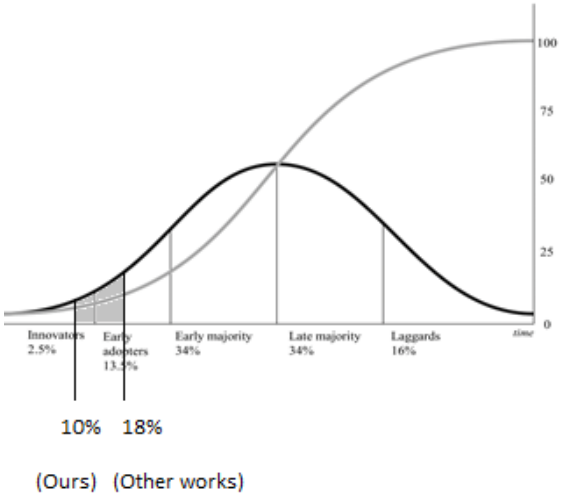


Figure 3. Estimation of the relative frequency of Brazilian adopters of PA application tools

CONCLUSION

Precision agriculture (PA) is a technological and managerial system that incorporates tools responding to users' needs and opportunities recognized by business agents. The wide variety of agricultural crops, soil and

climate conditions, land tenure and agricultural management models have made PA adoption in Brazil an uneven process with relevant differences.

This work sought to carry out a systematic review of previous publications focused on PA complemented with a meta-analysis. Given the heterogeneity found in the views in the published works, a complementary analysis was carried out of the responses obtained from ten experts at the largest Brazilian business fair on precision agriculture. Thus, the adoption of *diagnostic* or *application tools* for PA is at a level of development associated with the *early majority* phase of these innovative processes.

The measure of several dimensions of PA adoption is still an open issue (Tables 2 and 3). Several authors consider PA as a technological system. A possible way to address these problems of assessment is to establish a unified taxonomy for the several levels of PA adoption and to distribute them into the functional categories assessed as subsystems. This method of measuring PA adoption can generate important contributions for further studies on this topic.

For further investigation, this work suggests the study of the hypothesis that these subsystems may comply with some sort of hierarchy, working as a “river lock system”, in which the adoption of core technologies of a subsystem is needed for the adequate adoption of technologies of the next subsystem.

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APPENDIX A

A META-ANALYSIS CONSIDERING PUBLICATIONS ABOUT PRECISION AGRICULTURE IN BRAZIL

As a constructive step in the analysis, a meta-analysis of published studies focused on the adoption of "Precision Agriculture" in Brazil was developed. According to the literature on meta-analysis (Govindan et al, 2020; Maki et al, 2019; MacKinnon et al, 2016), the purpose of a meta-analysis goes through three main objectives. The first objective is to find a confidence interval for these estimates, considering the various results for a given phenomenon. The second objective is to analyze the heterogeneity related to the various studies. Finally, the variation in studies attributable to heterogeneity is calculated, that is, how the number of observed individuals (which varies throughout the studies), influences the estimates reached.

The methodological steps associated with performing a meta-analysis are detailed in the works of Maki et al. (2019) and Figueiredo Filho et al. (2014). Generally, these steps are as follows:

1. Identify/formulate the research problem
2. Select the relevant literature (books, articles, theses, unpublished articles, etc.)
3. Collect information from each study
4. Assess the quality of studies
5. Analyze and summarize the results of the studies
6. Interpret the data obtained
7. Display search results

Thus, based on the 5 published studies on the Adoption of Precision Agriculture in Brazil, two meta-analysis exercises were carried out – an exercise on the adoption of *diagnostic tools* and another exercise on *application tools*. Figure A.1 and Table A.1 summarize the main results achieved for the meta-analysis on diagnostic tools.

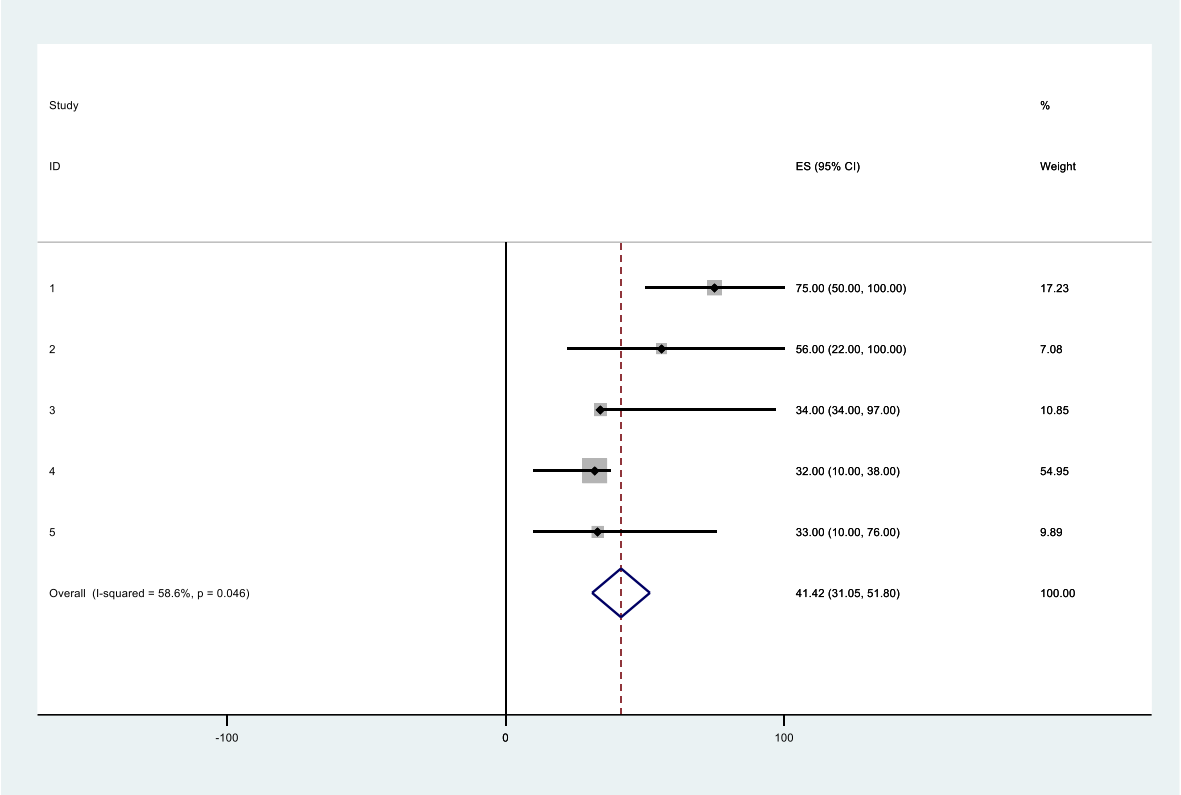


Figure A.1. Forest plot of diagnostic tools (effect sizes upon weighted relative frequencies)

Note. Study ID – 1: Pinto, Ferreira, & Teixeira (2017); 2: Borghi et al. (2016); 3: Soares Filho & Cunha (2015); 4: Bernardi & Inamasu (2014); 5: Silva, Moraes, & Molin (2011).

Table A.1

Diagnostic tools (effect sizes upon weighted relative frequencies)

Study	ES	[95% Conf. Interval]	% Weight
1	75,000	50,000-100,000	17.23
2	56,000	22,000-100,000	7.08
3	34,000	34,000-97,000	10.85
4	32,000	10,000-38,000	54.95
5	33.000	10,000-76,000	9.89
1-5 pooled ES	41.425	31,407-51,802	100.00

Heterogeneity calculated by formula: $Q = \Sigma i\{ (1/\text{variance}_i)*(\text{effect}_i - \text{effect_pooled})^2 \}$

where variance $i = ((\text{upper limit} - \text{lower limit})/(2 \times z))^2$

Heterogeneity $\chi^2 =$ 9.67 (d.f. = 4), $p = 0.046$

I^2 (variation in ES attributable to heterogeneity) = 58.6%

Test of ES = 0: $z = 7.82$, $p = 0.000$

```
Study    |    ES    [95% Conf. Interval]    % Weight
---------------------+--------------------------------------------------
1                | 75.000     50.000 100.000        17.23
2                | 56.000     22.000 100.000        7.08
3                | 34.000     34.000   97.000        10.85
4                | 32.000     10.000   38.000        54.95
5                | 33.000     10.000   76.000        9.89
---------------------+--------------------------------------------------
I-V pooled ES        | 41.425     31.047   51.802        100.00
---------------------+--------------------------------------------------
```

In a combined reading of Figure A.1 and Table A.1, the confidence interval for the percentage of respondents who assumed the adoption of “Diagnostic Tools” is between 31.05% and 51.80%. Clearly, the study

by Borghi et al. (2016) is the one with the largest range of variation in responses, while Bernardi & Inamasu (2014) is the study with the smallest range of variation.

In terms of heterogeneity, the focus was on two statistics revealed in Table A.1 - I-V and heterogeneity χ^2. The literature focused on these statistics is the work of Higgins et al. (2003).

The homogeneity of results is extremely important in order to give credibility to both their consistency and the intended generalization for the problem proposed through the studies used. On the other hand, in a meta-analysis, the variation in results between studies constitutes an element for discussing heterogeneity (Higgins et al., 2003).

A test of heterogeneity examines the null hypothesis that all studies evaluate the same effect. The Cochran *Q* test is the most common and is calculated by adding the square of the differences between the individual effects of each study and the combined effect of all studies, giving each study the same weight as in the meta-analysis itself. The *p*-value is obtained by comparing statistics with an X^2 distribution with *k*-1 degrees of freedom, where *k* is the number of studies. The power of the *Q* test to understand heterogeneity is low when the number of studies used is also low. The same applies in reverse: when the number of studies used is very high, the power of the test is excessive, since even if there is a small inconsistency between the results, the conclusion of the work was not affected by Higgins et al. (2003).

Therefore, to determine whether the differences in the results are genuine (heterogeneity) or whether they are compatible with chance alone (homogeneity), Higgins et al. (2003) developed an alternative approach, namely I^2, which describes the percentage of the total variance between studies that is caused by heterogeneity and not by chance.

$I^2 = 100\% \times ((Q\text{-}df))/Q$, where *Q* is the Cochran heterogeneity statistic and df is the degrees of freedom. Negative values of I^2 are equal to 0, so I^2 ranges from 0 to 100%. A value of 0% indicates that heterogeneity is not observed and values closer to 100% show significant heterogeneity in the studies, which reveals that the same studies observed significantly different individuals.

In this first exercise, $I^2 = 59\%$ (<75%), which proves that despite the time difference between the studies, the samples observed converge in the characteristics of the individuals observed.

This result follows the estimated value for "heterogeneity χ^2", which "assesses whether observed differences in results are compatible with chance alone. A low *p* value (or a large χ^2 statistic relative to its degrees of freedom) provides evidence of heterogeneity of intervention effects (variation in effect estimates beyond chance)" (Higgins and Green, 2011). Thus, the achieved value (Table A.1) was 9.67 (d.f. = 4), corresponding to a

p-value of 0.046; thus, there is a low probability that these results were achieved by random observations, which proves the convergence of values.

Just as the previous exercise regarding the adoption of "Diagnostic Tools" was performed, a similar exercise regarding the adoption of "Application Tools" identified for "Precision Agriculture" was done. Figure A.2 below shows the analysis of the dispersion of the adoption frequencies in each study as well as the estimate for the central value. Table A.2 Table details these values.

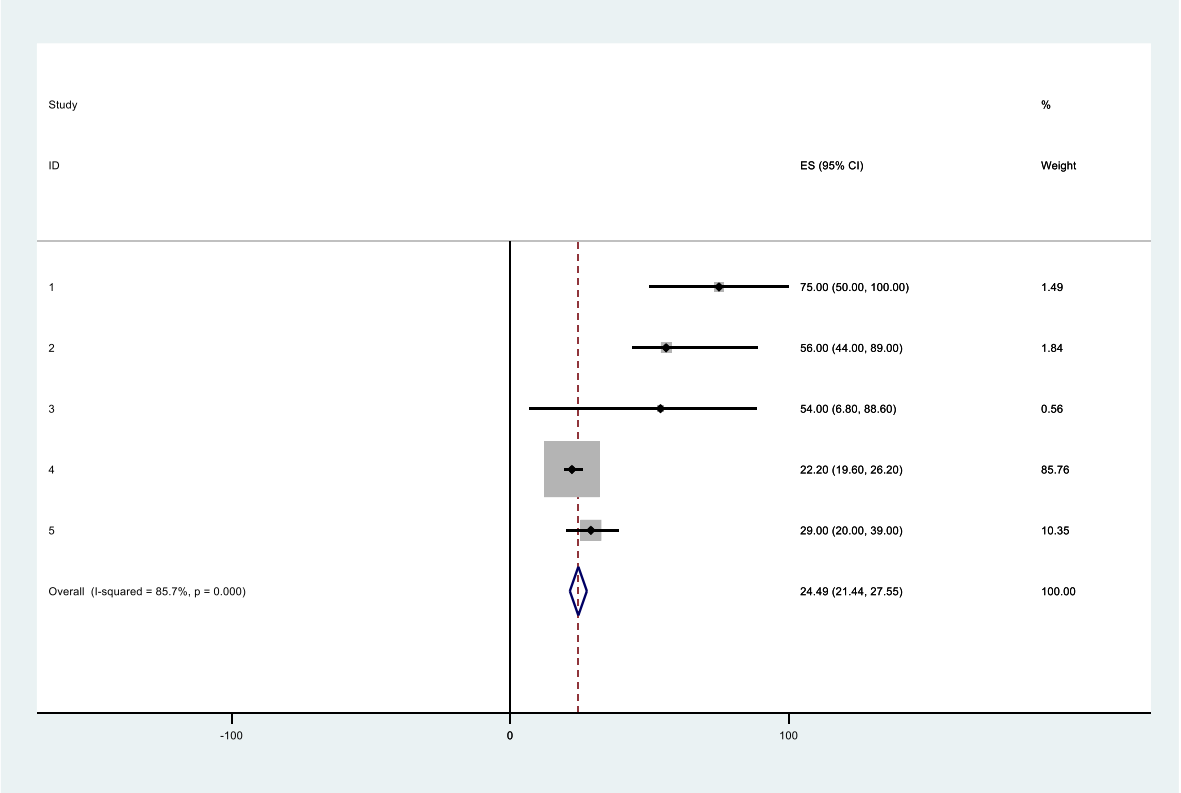


Figure A.2. Forest plot of application tools adoption (effect sizes upon weighted relative frequencies)

Note. Study ID – 1: Pinto, Ferreira, & Teixeira (2017); 2: Borghi et al. (2016); 3: Soares Filho & Cunha (2015); 4: Bernardi & Inamasu (2014); 5: Silva, Moraes, & Molin (2011).

Table A.2

Application tools adoption (effect sizes upon weighted relative frequencies)

Study	ES	[95% Conf. Interval]	% Weight
1	75,000	50,000-100,000	1.49
2	56,000	44,000-89,000	1.84
3	54,000	6,800-88,600	0.56

4	22,200	19,600-26,200	85.76
5	29.000	20,000-39,000	10.35
1-5 pooled ES	24.494	21,438-27,550	100.00

Heterogeneity calculated by formula: $Q = \Sigma i\{ (1/\text{variance}_i)*(\text{effect}_i - \text{effect_pooled})^2 \}$

where variance $i = ((\text{upper limit} - \text{lower limit})/(2 \times z))^2$

Heterogeneity $\chi^2 =$ 27.93 (d.f. = 4), $p = 0.000$

I^2 (variation in ES attributable to heterogeneity) = 85.7%

Test of ES = 0: $z = 15.71$, $p = 0.000$

Study	ES	[95% Conf. Interval]	% Weight
1	75.000	50.000 100.000	1.49
2	56.000	44.000 89.000	1.84
3	54.000	6.800 88.600	0.56
4	22.200	19.600 26.200	85.76
5	29.000	20.000 39.000	10.35
I-V pooled ES	24.494	21.438 27.550	100.00

In a combined reading of Figure A.2 and Table A.2, the expected adoption of application tools in Brazilian Precision Agriculture is less than that identified by the same studies in relation to diagnostic tools. The expected central value considered by the meta-analysis on the studies in question is 24.49, which suggests that the Brazilian economy is at less advanced stages in the adoption of application tools than in the adoption of diagnostic tools.

In this second exercise, I^2 = 86% (> 75%), which proves an increase in the influence of the observed heterogeneity. This result follows the estimated value for the heterogeneity χ^2. Thus, the achieved value (Table A.2) was 27.93 (d.f. = 4), corresponding to a *p*-value of 0.000; thus, there is a low probability that these results were achieved by random observations converging with the previously concluded one.

For a summary of this meta-analysis – the first meta-analysis effort made on published studies in relation to precision agriculture – the following is suggested. It focused on the 5 previously published studies on the adoption of diagnostic tools and application tools in Brazil. This effort made it possible to conclude by reaching a more advanced phase of the adoption of diagnostic tools in relation to the adoption of application tools. However, the heterogeneity of the same studies has also been proven and this requires special attention when commenting on these studies.

APPENDIX B

RESPONDENTS' EVALUATIONS OF

PRECISION AGRICULTURE ADOPTION IN BRAZIL

Table B.1

Respondents' Evaluations of Precision Agriculture Adoption in Brazil

Respondent	High	Medium	Low	Evaluation
1I	X		X	"the level of PA adoption in Brazil is low, [...] for the lack of knowledge of what is precision agriculture strictly, its concepts, and for the PA itself in Brazil, not only in Brazil, [...] has part of the homework to be done, to prove that its techniques are efficient. [PA adoption] *may be considered high* in terms of agricultural mechanization. Therefore, automated agricultural implements, but for me this is not PA, this is crop mechanization." "To my knowledge, I am making an estimation off the top of my head, I would say that 70% of the harvesters that have a productivity sensor, the sensors are not even turned on."
2I		X		"I believe it is in a transient stage, from *low to medium*. [...] mainly because […], we can transmit more information than we could 20 years ago. [...] The producer has also a f ear to adopt something new. The adoption curve starts to climb up very slowly. However, I believe that today this curve is halfway. Because farmers now can see the outcomes of the early adopters, they are already presenting results."
1A		X		"*medium*, because there is already a community of users. The numbers, the few numbers we already have point out to 15 to 20% of the farmers already using things from precision agriculture core. That's big."
2A		X		"I would say that some crops, for instance, grains, already have a *medium* level of adoption. At most medium and it is very dependent [...], for some purposes it is more adopted, for others it is less adopted. [...] The adoption seldom occurs thoroughly, that means, one uses the

				complete process of precision agriculture.”
3A	X			“adoption in Brazil is considerably *high*. Why? Because farmers could see the value of those technologies. They are also very simple technologies. Thus, they do not require too much science, the farmer does not need to know many things to adopt those technologies. It is what we call ready-to-use technologies. In Brazil, they are considerably adopted, only the big business groups [...]” “I believe those technologies already found the curve plateau, they are already adopted. Sure, there are always the laggards. However, I think the early adopter phase is over, we are in the mass adoption phase. Therefore, it is over, it is already in *40, 50, 60% of adoption*.” “Currently, *about management, I think we are in the innovators phase, maybe going to the early adopters. Thus, if you look here, 15% of the farms are already adopting PA.*”
1CS			X	“a very particular point of view, of a service provider [...]. I think the adoption of precision agriculture technologies is still **low**, but there is a trend, the farmer is becoming aware of the benefits of adopting those practices to effectively increase his yield. [...] currently, many Brazilian farmers do not practice even conventional agriculture, which means to analyze the subsoil, as a minimum parameter in order to get any recommendation. [...] I cannot say in numbers what it represents, maybe *12, 15% of the market that adopts precision agriculture*. They are already in a more technified level to use this sort of technology, but I suppose that not even 50% of the farmers do not make a simple analysis, a simple diagnosis, that is soil analysis [...]. Therefore, in general terms of the market, the level of adoption is *low*, but there is a tendency of the new generation and of who already adopts this sort of technology to use it more and more.”

2CS	--			"I think the adoption level of the technology comes from a certain expertise in the area, we are in a digital age, and there is a strong tendency of family succession and young farmers want their properties on the tip of their fingers. [...] we are following this expansion and believe it is in the right way. [...] About precision agriculture, there is a wide range of operation and evaluation types." "our variability of soils, property sizes, management techniques, crops [...] is huge. Therefore, it provides us with a very large expertise to provide different technologies in order to deal with those variabilities."
3CS	X			"our level of adoption is *high*. [...] what calls the attention of the farmer is better results. [...] And precision agriculture clearly gathers data together. It brings all information you need, but the presentation of this information is not enough to make a quick and assertive decision, which is what the farmer truly needs. [...] and we see some barriers for this adoption, mainly the digital thing, because many times the customer feels the need, but they cannot identify their real need." "We have big data in agriculture for quite some time. Precision agriculture is already in the field, the machines, [...] we have much data, but the customers do not know what to do with these data. In addition, data itself is valuable, but if it is presented wrongly, if it does not generate the *insight* the customer truly needs, he cannot do anything with that data." "many farmers still live in the 'paper' age." "this journey to engage in the adoption of precision agriculture to achieve digital agriculture [...]. You should make certain changes in your whole team and in the processes. Many times, they see this as a barrier. Thus, perhaps this hinders slightly the engagement, but it is as I should speak again, when we talk about the benefits and we present cases of success, we can engage better those customers."

1 M			X	“we believe that it is a *low* level. Therefore, it reflects the adoption of machines but also the issue about consultancy. [...]. However, currently, for instance, if you talk about PA, you are talking about many fields. [...] Therefore, about the evaluation of what is the use of PA. [...] a farmer, he already uses variable rate application, for instance, of fertilizers, another farmer uses automatic pilot, another uses another technology. Therefore, it happens to be the use of PA. However, it is not the ‘whole’ PA”. [...] “there are much smaller research studies that seek this measure. However, in Brazil, we have a need for this. Therefore, we are waiting anxiously, companies are waiting, the market is waiting, farmers are waiting. [...] Currently, this number is vague. [...] So an interesting number will show up, which will be used as a basis for companies, farmers, and the government.”
2 M			X	"it is very segmented, we have the big farmers, that [...] see precision agriculture as [...] interesting, but we have a huge barrier among medium and small farmers, they still see it as a cost, not as an investment to gather more information. [...] as we have many more small and medium farmers than the big ones, if we consider the level of adoption in general, I still think it is *very low* in Brazil.”

Note. Source: prepared by the authors. Answers were collected in Portuguese.

APPENDIX C

OTHER SUPPORT TABLES

Table C.1

Relative frequencies of respondents recognizing the use of PA application tools

	Application					
Authors	n	Automatic pilot	GPS guidance with auto control/autosteer	Guidance system with manual control/lightbar	Satellite guidance system	Variable rate technologies
Pinto, Ferreira, & Teixeira (2017)[1]	105	--	--	Yes	--	Yes
Borghi et al. (2016)	25[2]	--	56%	89%	--	--
Soares Filho & Cunha (2015)	43	68.18%	--	54.55%	--	88.64%
Bernardi & Inamasu (2014)	301	--	19.56%	22.21%	--	26.18%
Silva, Moraes, & Molin (2011)	87	--	39%	--	20%	29%

[1]This sample is of PA adopters; besides that, this study mentions technologies, but does not evaluate how many farmers adopt them.

[2]All respondents consider themselves as PA adopters.

Table C.2

Relative frequencies of respondents recognizing the use of PA diagnostic tools

	Diagnostics							
Authors	n	Grid soil sampling[1]	Georeferenced soil sampling[1]	Soil/productivity maps	Satellite images	Harvest/Yield monitor (using GIS or not)	Remote sensing (including GPS)	On-the-go sensor

Pinto, Ferreira, & Teixeira (2017)[2]	105	Yes	--	Yes	--	--	Yes	--
Borghi et al. (2016)	25[3]	100%	--	100%	22%	56%	22%	22
Soares Filho & Cunha (2015)	43	97.73%	--	--	34.09%	47.73%	--	--
Bernardi & Inamasu (2014)	301	--	38.11%	--	--	10.28%	--	--
Silva, Moraes, & Molin (2011)	87	--	31%	--	76%	10%	--	--

[1]Only "soil sampling" was mentioned, but with no specification (grid or georeferenced). Therefore, a value of 10% was assumed for b

[2]This sample is PA adopters; besides that, this study mentions technologies, but does not evaluate how many farmers adopt them.

[3]All respondents consider themselves as PA adopters.

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