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ANALYSIS OF THE TECHNOLOGICAL INNOVATION SYSTEM IN PRECISION AGRICULTURE IN BRAZIL

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ABSTRACT

The present study aimed to investigate the operation of innovation activities in precision agriculture in Brazil, from the viewpoint of the technological innovation system, based on the functions established in the literature on this topic, analyzing each function and the interactions between functions. To do so, it followed the theoretical framework of evolutionary economics and the consequent framework of innovation systems, centered on the technological innovation systems perspective, based on a methodological approach that considered aspects of quantitative research, with the application of 217 questionnaires. The results indicate that precision agriculture is in the development stage in Brazil, with a greater role of the systemic function of knowledge exchange. The conclusions show that the relation between functions varies according to the technology under analysis and due to external factors that interact with it. Besides the technology development phase, and it is not possible to establish a fixed standard, as proposed in the literature.

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INTRODUCTION

Since the adoption in 2015 by the United Nations General Assembly of Resolution 70/1, entitled "*Transforming our world: the 2030 Agenda for Sustainable Development*", or simply Agenda 2030, "an action plan for people, the planet and prosperity "(United Nations [UN], 2015, p. 1), the discussions on the need for action by governments on an issue long debated by Thomas Robert Malthus (1766-1834) and neo-Malthusian theorists, albeit with questionable arguments: food shortages. In Brazil, the National Strategy for Science, Technology and Innovation (ENCTI) for the period of 2016 to 2022, prepared by the Ministry of Science, Technology, Innovations and Communications of Brazil (MCTIC, 2016), presents the availability of food as one of the main topics of the Brazilian National Science, Technology and Innovation System (SNCTI). The food sector is highlighted in ENCTI as one of the strategic themes for national development, with which SNCTI has increasing responsibilities for the sustainable increase of its agricultural production, from the development and improvement of sustainable integrated productive systems and the development and application of new technologies capable of generating increased productivity, while at the same time improving the use of natural resources applied to the productive process, such as land, water and energy. Faced with this challenge, the ENCTI document points to the need to strengthen research, development and innovation (RD&I) processes in frontier areas of knowledge associated with food production, such as biotechnology, bioinformatics, nanotechnology, modeling, simulation and automation, aiming at increasing productivity, adaptation to climate change and agricultural defense, where the precision agriculture model gains considerable prominence, cited in the document itself, by the convergence of management technology, information technology and value added to production, with minimization of environmental impacts. According to Bernardi *et al*. (2014), RD& I's efforts in precision agriculture in Brazil are structured in a network, organized and led by Embrapa, which brings together about 200 researchers, 20 Embrapa research centers, more than 30 private companies, nine universities, three foundations, four research institutes, and a National Reference Laboratory in Precision Agriculture (Lanapre), operating in 15 experimental fields of perennial and annual crops, distributed throughout the national territory. In this study, the use of a precision-based agriculture network (AP network), suggests the existence of a technological system in Brazil (CARLSSON; STANKIEWICZ, 1991; HEKKERT *et al*., 2007; HEKKERT., 2011). However, the innovative process related to the development of new technologies is quite complex and requires great effort from public and private organizations in the implementation of research, development and innovation infrastructures that favor the establishment of relations for the exchange of knowledge necessary for innovation generation and diffusion (SALERNO; KUBOTA, 2008). Given the structures and relationships put in place, it is necessary to reflect on how the technological innovation activities in this field have worked in the face of the challenges that are presented for Brazilian agricultural production. Thus, the research had the objective of investigating the operation of innovation activities in precision agriculture in Brazil, under the optics of the technological innovation system, analyzing each function and the interactions between functions. The study of these structures and working patterns can contribute to the more efficient performance of public policy makers as well as public and private actors who act or wish to work in this field, both in Brazil and in other countries with similar characteristics, based on the Brazilian example. In addition, a major step towards the advancement of technological development is the recognition of the weaknesses and potentialities that permeate its environment at the present moment, with a view to implementing more assertive policies towards the future of technology, to which it is hoped that this study can contribute also in this sense.

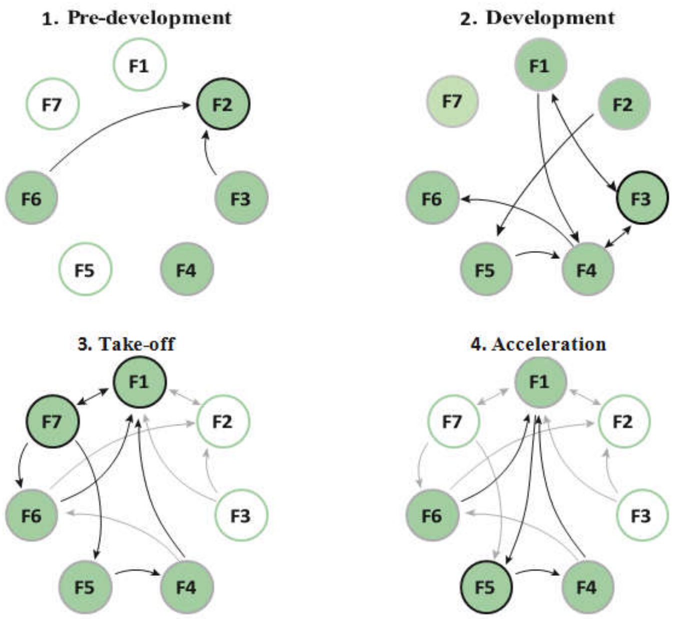
The Functions of Technological Innovation Systems: Carlsson and Stankiewicz (1991, p. 94) define a technological innovation system as "a dynamic network of agents interacting in the economic/industrial areas, under a particular institutional infrastructure and involved in the generation, diffusion and use of a specific technology." Within the theoretical frameworks of innovation systems, the design of a technological system is considered by some authors (CARLSSON; STANKIEWICZ, 1991; CARLSSON *et al*., 2002; JACOBSSON; BERGEK, 2004; HEKKERT *et al*., 2007; HEKKERT; NEGRO, 2009; HEKKERT *et al*., 2011; SANDÉN; HILLMAN, 2011) as more appropriate to explain technological changes brought about by the innovation processes, since its analysis occurs at a micro, less complex level. Technological innovation systems, or simply technological systems, were proposed by Carlsson and Stankiewicz (1991) as an alternative to the geographical delimitation present in the definition of national innovation systems. Thus, the definition of a technological system coined by the authors is based on the premise that their limits may or may not coincide with national boundaries, but may also vary from one techno-industrial area to another depending on the economic agents participating in them. In this way, a technological system can be defined as the set of actors, networks and institutions (laws and rules) that, when interacting with each other, influence the speed and direction of technological change in a specific technological area (HEKKERT *et al*., 2007; BERGEK *et al*., 2008; MARKARD; TRUFFER, 2008). According to Wieczorek *et al*. (2015), this set of actors, networks and institutions form the structural components of technological systems, following the more general structures of innovation systems. An innovative and essential aspect of the technological system perspective refers to its attention to the functional performance of the system components, conceptualized through a set of seven functions summarized in Table 1, defined in two programmatic works by Hekkert *et al*. (2007) andBergek *et al*. (2008).

Table 1. Functions of technological innovation systems

Functions	Definition
F1. Entrepreneurial Activities	The activities carried out by the entrepreneurs who are part of the system, including commercial experiences, demonstration of R&D and openness for entry of new companies.
F2. Knowledge development	The basic research and technology discovery created by R&D investments and activities, prerequisites for innovation.
F3. Knowledge Exchange	The process that knowledge and technology are transferred from one network or organization to other networks or organizations.
F4. Research Guidance	The necessary direction to facilitate convergence in technological development, involving political goals and expectations about technological options.
F5. Market formation	The formation of a new market or niche market, creating temporary competitive advantage through favorable tax regimes, consumption quotas or other public policy activities.
F6. Mobilization of resources	The investment in human capital, financial capital and infrastructure, which were incorporated by the government, venture capital or financial companies.
F7. Creation of legitimacy	Government, legal coalition and public support to technology to combat resistance of established actors, as well as the willingness of companies to support the maturing of the projects developed.

Source: Adapted from Van Alphen *et al*. (2010) and Lai *et al*. (2012).

System functions are a series of processes or activities considered by the authors as of extreme importance for the proper functioning of an innovation system (HEKKERT *et al*., 2007). The mapping of these processes allows analyzing the dynamics of a technological innovation system, with practical guidelines of what is contributing to the advancement of innovative technology and what is slowing its evolution (BERGEK *et al*., 2008). The main contribution of this analysis approach revolves around the notion of cumulative causality between the technological system functions, which reinforce each other over time. However, in the same way that they complement each other, an innovation system can collapse due to the absence of a single function of this system (SUURS *et al*., 2010; LAI *et al*., 2012). This complementation establishes certain functional patterns according to the development phase of the technology being analyzed. Thus, the importance attributed to the functions will be different in each phase, given the need of the system at that time for the development of the technology (HEKKERT *et al*., 2011). A schematic of this relative importance can be seen in Figure 1. The black arrows are the relations that occur in the current phase, whereas the gray arrows represent the relations that occurred in previous phases and are still occurring to improve the development of the technology, since the knowledge is accumulated in each phase. Functions with bold circles represent the most important function for that phase. For example, in the pre-development phase, characterized mainly by the development of experimentally tested prototypes under controlled conditions, knowledge development is the most important function, critically influenced by the functions of knowledge exchange and mobilization of resources, which give support to the main function, given that research orientation is a critical function for the mobilization of resources.



Fonte: Hekkert *et al*. (2011).

Figure 1. Functional patterns by technology development phase

In the development phase, it is expected that the entrepreneurial activity is the most important function in the system, since the first experiences have already been carried out, which will show if the innovation also works in practice. This demands that the knowledge development function remains active. However, all other system functions can positively or negatively influence this function, so all can be critical at this stage and need to be carefully analyzed (HEKKERT *et al*., 2011). Some of the main criticisms of this perspective are the fact that it was conceived and applied in developed countries and that developing countries generally have a low level of development of the various technological system functions. In addition, it is argued that the frontier of the technological system itself ignores exogenous factors that may influence the performance of functions, especially in developing countries (EDSAND, 2017). Despite this, studies in this line of approach have been successful in countries such as Ethiopia (KEBEDE; MITSUFUJI, 2017) and China (CHEN; ZHAO, 2012; LAI *et al*., 2012), suggesting that the use of multilevel approaches, also considering the historical facts related to the technology and the institutional context in which the actors are inserted, can minimize this apparent limitation of the approach (BERGEK *et al*., 2008, HEKKERT *et al*., 2011).

In precision agriculture surveys, the technological systems approach was recommended by Eastwood, Chapman and Paine (2012) for better visualization of the actors involved in the innovation process. Later on, it was used by Eastwood, Trotter and Scott (2013) to address the current challenges to successful precision farming in the Australian dairy, beef and sheep industry, and by Eastwood, Klerkx and Nettle (2017) when analyzing the division of the research functions as well as public and private extensions into agricultural innovation systems. According to Bernardi *et al*. (2014), RD&I's efforts in precision agriculture in Brazil are structured in a network, organized and led by Embrapa, which brings together about 200 researchers, 20 Embrapa research centers, more than 30 private companies, nine universities, three foundations, four research institutes, in addition to a National Reference Laboratory in Precision Agriculture (Lanapre), operating in 15 experimental fields of perennial and annual crops, distributed throughout the national territory. Referred to as Precision Agriculture Network (or AP Network), such a configuration suggests the existence of a technological system (CARLSSON; STANKIEWICZ, 1991; HEKKERT *et al*., 2007; HEKKERT *et al*., 2011) tied to innovation activities in precision agriculture in Brazil.

In this way, the following research hypotheses are formulated:

H1: Precision agriculture technology is in the development phase in Brazil.
H2: Entrepreneurial activity is the most influential function of the system.
H3: There is a positive correlation between entrepreneurial activity and knowledge development.
H4: Knowledge exchange positively influences the entrepreneurial activity.
H5: The orientation of the research positively influences the entrepreneurial activity.

Given the food and climate change challenges that motivate different innovation research in agriculture, the perspective of agricultural innovation systems appears as an important catalyst in minimizing the contingencies of the emerging agricultural scenario. With a systemic view of innovation, one can favor, for example, technologies that are less aggressive to the environment, a paradox of agriculture in any global context.

MATERIALS AND METHODS

In order to investigate the systemic functioning of innovation activities, based on the seven functions of the technological innovation system (HEKKERT *et al*., 2007; VAN ALPHEN *et al*., 2010; LAI *et al*., 2012), based on the perception of actors involved in this environment on a daily basis, on how well each function has been executed and the influence thereof for the development of precision agriculture technology, a field survey was carried out with the application of an electronic questionnaire (GIL, 2008; HEKKERT *et al*., 2011), in which the participation of the largest possible number of actors involved in research and innovation activities was sought by sending the questionnaire link to all members of the AP Network, to the members of the Brazilian Precision Agriculture Commission, the Brazilian Association of Precision Agriculture Service Providers (ABPSAP) and the Brazilian Association of Precision Agriculture (AsBraAP), for sharing among its associates, and to the graduate programs of universities with a line of research in the area of precision agriculture, for sharing among its researchers.

Because it is a highly dynamic environment in which there is no estimated number of participating actors, the definition of a sample size, whether random or not, has proved to be impractical and, on the face of it, to try ensuring that respondents were actually involved with the object of study and connoisseurs of the innovation dynamics that was sought to design, was the only concern carried out to ensure the scientific validity of the data. To that end, the involvement of sectoral associations played an active role in the research dissemination and in the results achieved with the online questionnaire, which returned a total of of 231 responses, of which 14 were discarded because they did not answer the entire questionnaire, leaving the total of 217 responses considered valid for data analysis and treatment. The instrument used was adapted from Hekkert *et al*. (2011). In it, each system function is a set of variables for punctuation assignment. This instrument (Appendix I) underwent a reverse translation of the English language into Portuguese and, later, by validation with a jury of experts formed by three Ph.D. professors who work in the Advanced Course of Technology in Mechanization in Precision Agriculture of FATEC Pompéia (SP). We included in the questionnaire information that identified the respondent's profile, such as time spent on innovation and precision agriculture, schooling and type of organizational link. Following the instrument, the system functions (CARLSSON; STANKIEWICZ, 1991; HEKKERT *et al*., 2007; BERGEK *et al*., 2008; HEKKERT *et al*., 2011; EASTWOOD; KLERKX; NETTLE, 2017) were scored by respondents in a 5-point Likert scale (1 = very weak and 5 = very strong) to identify how well each function is fulfilled and which functions constitute the greatest difficulty or the greatest support for activities.

The functions of the system with the lowest scores can be seen as the most problematic. The data treatment was performed using the Statistical Package for the Social Sciences (IBM® *SPSS*® Statistics version 18) software, in which a descriptive statistical analysis of the data with an overview of the fulfillment of each function was verified, as well as the establishment of correlations between the system functions and the development phase of the technology, besides analyzing the functions as set of independent variables capable of explaining a proportion of technology development variation, as a dependent variable, at a significance level, applying the linear regression analysis technique using the Enter method (HAIR *et al*., 2009; GOUVÊA; PREARO; ROMEIRO, 2012). Among the assumptions to be considered for the application of multiple linear regression analysis are the absence of multicollinearity, the multivariate data normality and the sample size, which is estimated in at least five observations for each independent variable in the statistical variable, which would give a sample of at least 160 (32 assertive x 5) cases for the applied questionnaire, and this premise is fully met by the quantitative analysis (HAIR *et al*., 2005). The absence of multicollinearity was confirmed with VIF values <5 and the multivariate data normality with the Kolmogorov-Smirnov test ($p = 0.000$).

RESULTS

The data analyzed aim to understand the systemic functioning of innovation activities from the seven technological innovation system functions designed by Hekkert *et al*. (2007), considering the perception of the different actors involved daily in this environment. For this, the respondents' profile is presented as a way of qualifying the data collected, and the main results obtained from the methodological techniques chosen for the analysis.

Respondents' profile: Among the information that qualifies the profile of the 217 respondents considered valid for the study is the type of organizational link in relation to the technology under analysis, in which 40% of them develop their activities as a teacher/researcher or graduate student in the area of precision agriculture in universities. Another 20% work in government agencies as formulators or executors of public policies, 17% are researchers linked to research institutes, 10% are professionals working in the machinery and agricultural implements industry, 7% are consultants providing services in precision agriculture and another 6% are representatives of support organizations. Among the link options was the technology user profile as a producer or cooperative, but there was no respondent with this type of link. Also asked about their schooling at the present time, 60% of the respondents are studying or have completed *StrictoSensu* (master's or doctoral) postgraduate studies, 36% have completed post-graduate *LatoSensu* (specialization) and 4% have completed higher education. A summary of this profile is presented in Table 2. Knowledge sharing is considered problematic by 62% of the respondents, while 67.74% of respondents consider this to be a barrier to technology advancing the next phase of development. This is due in particular to the relationship between industry and users, perceived to be weak by 67% of respondents, and the weak relationship between actors across geographical boundaries, perceived to be weak by 61.29%, indicating the concentration of knowledge developed in geographic pockets.Respondents also indicated that knowledge exchange between research and industry is weak (74%), but, as seen in the qualitative stage, this exchange is indeed restricted to a dominant group, not necessarily weak but problematic in this sense. The correlation test indicated the existence of a positive correlation between the development phase of precision agriculture technology and the system functions analyzed by the instrument, except creation of legitimacy. The regression results indicate a moderate adjustment of the model, with $R^2 = 0.435$ and R^2Ajusted = 0.416. The value of the *Durbin-Watson* test = 1.941, indicates absence of self-correlation of residues. This result means that at least 41.6% of the development of the technology can be explained from the independent variables listed in the model.This moderate adjustment is acceptable considering that this study is not intended to predict, but only to investigate the functioning of the functions. In addition, the complexity of technological innovation as an object of study is something that would require a more in-depth analysis if the objective were the prediction. Table 3 shows the regression coefficients.

Table 2. Respondents' profile

Organizational link			Schooling		
Service provider	15	6,67%	ElementarySchool	0	0%
Industry	22	10%	High school	0	0%
University	87	40%	Highereducation	8	3,33
Researchinstitute	35	16,67%	Lato Sensu postgraduateeducation	79	36,67%
Governmentagency	43	20%	Stricto Sensu postgraduateeducation	130	60%
Supportorganization	15	6,67%	Outro		
User	0	0%			
Others	0	0%			

Fonte: Author'selaboration

Table 3. Regression Coefficients

General model	Standardizedcoefficients	t	Sig.	Diagnosisofcollinearity	
	Beta			Tolerance	VIF
(Constant)		-4,158	0,000		
Entrepreneurialactivity	0,250	3,883	0,000	0,651	1,537
Knowledgedevelopment	0,072	1,207	0,229	0,762	1,312
Knowledgeexchange	0,657	9,058	0,000	0,514	1,945
Researchorientation	-0,280	-3,611	0,000	0,449	2,228
Market formation	-0,080	-1,346	0,180	0,764	1,309
Mobilizationofresources	0,110	1,843	0,067	0,760	1,316
Creationoflegitimacy	0,083	1,523	0,129	0,907	1,103

a. Dependent variable: Technology development phase
Source: Elaboration by author.

The regression data indicate knowledge exchange as the most influential function on the model, as opposed to the entrepreneurial activity, as expected and proposed by the H2 hypothesis. *Entrepreneurial activity is the most influential function of the system, indicating its rejection*. Aligned, knowledge exchange is a function that, at this stage, maintains a good positive correlation with the entrepreneurial activity (0,400 p = 0,000), another influential function in the model, which in turn also maintains a positive correlation with knowledge development 0.366 p = 0.000), suggesting the acceptance of the descriptive hypothesis H3. *There is a positive correlation between entrepreneurial activity and knowledge development*. The complete table of correlations is presented in Appendix II. In addition, the descriptive hypotheses H4, H5 are also acceptable, since the correlation results confirm this assumption forknowledge exchange (0,400 p = 0,000) and research orientation (0,439 p = 0,000), indicating that the entrepreneurial activity is favored in a scenario with direction on the path to be followed by technology, with strong exchange relationships and investments in infrastructure, qualification and access to capital. Among the functions with the best respondent perception is precisely the entrepreneurial activity, followed by knowledge development and market formation.In general, respondents consider that there is a strong or very strong entry movement of new companies (78.31%) and innovation among industries (45.17%), as well as perceiving the quality (61.29%) and quantity (58.06%) of knowledge developed as strong or very strong.

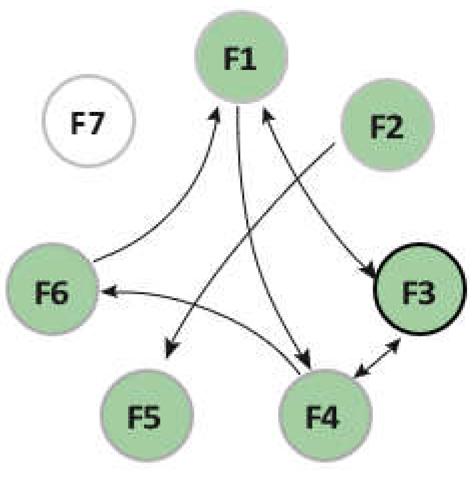


Figure 2. Functional technological pattern in the development phase

This indicates the need for adjustments in the other functions to respond to the system needs and technological development. From the correlation data between the investigated variables, which demonstrate the interdependencies between the system functions in its development phase, it became possible to visually propose how these interactions occur, reediting Figure 1, from Hekkert et al. (2011), presented in Figure 2. Figure 2 shows the knowledge exchange function (F3) as the most important function of the system (β = 0.657 p = 0.000), interacting mutually with the research orientation functions (F4: 0.674 p = 0.000) and entrepreneurial activity (F1: 0,400 p = 0,000), suggesting that there is a dynamic relationship of mutual feeding and feedback, both to stimulate the emergence of new businesses in the technological area and to define the directions to be followed by research and development.Research orientation (F4) also influences resource mobilization (F6: 0.407 p = 0.000) to be allocated to this field, which in turn influences the vigor of the entrepreneurial activity (F1: 0.360 p = 0.000), suggesting that the more resource mobilized for the area, the greater the possibility for new businesses to emerge. It is also interesting to note that the developed knowledge (F2) can act as the driver of the market in formation (F5: 0.366 p = 0.000).

DISCUSSION

The literature on functional patterns in Hekkert et al. (2011) suggests that with technology in the development phase, as identified for precision agriculture, it would be expected that the entrepreneurial activity would be the most important function, impelling the generation of assets that contributed to its advance. For this case, however, it was found that knowledge exchange of knowledge, which seems to make sense since a significant percentage of the knowledge necessary for the technology to reach this stage must have been developed in the previous phase and needs to overcome barriers through exchanges to generate application and growth. The identified correlation between the knowledge exchange and entrepreneurial activity functions, in turn, suggests that the relationships established in these exchanges can also favor the emergence of new companies, such as agro startups. An observation should be made in this regard, since the participants of the research pointed out that precision agriculture technology is in the development stage in Brazil, indicating if it is an incipient system, in which a greater role of public research organizations in the development of knowledge that makes commercial exploitation viable by private capital is expected, as suggested in Salerno and Kubota (2008), pointing out the lack of synergy between organizations in this sense, especially universities and private colleges and government agencies.

Conclusion

Regarding functional patterns in technological innovation systems, it should be clarified that their relations between functions and the influence of one on the other, seen in the conceptual referential, should not be taken as absolute truth. It seems plausible that, from what has been seen in this study, this relation varies according to the technology under analysis and due to external factors that interact with it, in addition to the development phase of technology, such as policies, infrastructures and the density of relationships between organizations. The main flaw seems to be political, weak institutional articulation that has not yet been able to include precision agriculture in the national strategic agenda, although it does appear in documents of the area of innovation. The system identified and analyzed contains all the constituent elements of a technological innovation system (industry, research, government, support organizations, etc.), but the general institutional apparatus and little specific and lack of political direction causes its performance to fall short of the desired. Precision farming is not deterministic in development. Governments and educational institutions need to be attentive to this context, because there is a need for interconnection between different areas of development, with consequences in different areas: education has repercussions on agriculture, which has repercussions on health, etc. This presupposes the understanding that the area is a complex system dependent on many variables that need to be recognized.

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