Journal of Rural Studies 89 (2022) 171–185

Contents lists available at ScienceDirect

Journal of Rural Studies

journal homepage: www.elsevier.com/locate/jrurstud

Connecting science, policy, and practice in agri-food system transformation: The role of boundary infrastructures in the evolution of Brazilian pig production

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ARTICLE INFO

Keywords:
Boundary work
Food systems transformation
Sustainability transitions
Intermediaries
Brazil
Agri-food sectors
Deep transitions
Directionality

ABSTRACT

Scholars have often applied the concept of boundary work and its conceptual progeny to explain how science, policy, and practice collaborate to introduce change into agrifood systems. However, previous studies focused primarily on specific boundary elements (i.e., boundary spanners, boundary organizations, and boundary objects) or particular innovation processes (in terms of scope or timescale) within broad transformative change. This study aims to deepen the understanding of long-term transformative processes in agri-food systems by looking at how boundary infrastructures influenced the evolution of the Brazilian pig production system from a setting in which it mainly produced pork lard for a domestic market to a setting of being integrated in global supply chains and following international standards. Mainly, we add to the extant literature by highlighting that boundary infrastructures influenced the longterm transformative process experienced by BPPS by establishing a space where science-policy-practice interactions legitimized particular visions and values and instilled responsibility and accountability to spur various joint actions in support of innovation. We also contribute to the extant literature by showing that boundary infrastructures evolution in BPPS was incremental, long-term, multi-site, and with intertwined leverage. Boundary infrastructures provide structuration to system transformation and are also (re)structured while transitions unfold. Since boundary infrastructures have a certain directionality and may become hegemonic and exclusionary, this requires sensitiveness to the need to reorient a hegemonic boundary infrastructure or create a parallel one. Our study deepens the understanding of how coordination unfolds in long-term transformative processes, a topic deemed of interest given current debates on promoting agri-food systems transformation. We argue that better awareness of boundary infrastructures in which science-policy-practice interactions occur can help guide the direction of innovation to support sustainability transitions in agri-food systems.

1. Introduction

Agri-food systems have undergone massive transformations worldwide in the last decades (Gollin et al., 2002; Li et al., 2019). In such long-term transformative processes, they have evolved from specific socio-technical settings[1] to new ones, often structured around more complex and broader configurations (Ingram, 2018; Šūmane et al., 2018). Varied phenomena have stimulated transformation over time and shaped the directionality of transitions, such as economic and market developments, technological breakthroughs, environmental impacts,

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[1] This study understands a socio-technical setting as interdependent material and social frameworks, such as policies, culture, technologies, or markets, which over time evolve into a dynamic stable configuration that enables the fulfilment of a societal function – e.g., see Fuenfschilling and Truffer (2014) and Geels and Schot (2010).

https://doi.org/10.1016/j.jrurstud.2021.11.025
Received 2 March 2020; Received in revised form 27 July 2021; Accepted 28 November 2021
Available online 4 December 2021

population growth, dietary changes, or societal demands (Darnhofer, 2015; FAO, 2019; Grin, 2010). Moreover, agri-food sectors' long-term transformative processes have often been deeply influenced by how interactions between science, policy, and practice[2] support innovation and enact directionality through a wide range of actions and interventions – e.g., innovation platforms, public development projects, and information networks (Ingram, 2015; Levidow, 2015; Pigford et al., 2018; Schot and Kanger, 2018), across several societal scales (de Boon et al., 2021).

Previous studies have regularly applied so-called 'boundary elements' to explain the roles of actions or interventions that enable change through innovation support in agri-food systems (Clark et al., 2016; Zougmoré et al., 2019). Such boundary elements (e.g., boundary work, boundary objects, boundary organizations) have been used as a theoretical and analytical lens to examine how people and organizations with different values, objectives, interests, and capacities team up under particular circumstances to cope with shared demands, challenges, and limitations that agri-food systems face (Franks, 2010; Turnhout, 2009; Betzold et al., 2018; Bos, 2009; Favilli et al., 2015; Tisenkopfs et al., 2015; Kristjanson et al., 2009; Sarkki et al., 2019). Mainly, extant work has described how specific boundary elements allowed collaboration between different actors who got involved in agri-food transformation processes but also sustainability transitions in general (Favilli et al., 2015; Steger et al., 2018; Franco-Torres et al., 2020) – e.g., functions performed by design process outputs (such as design briefs, scale models, visualizations, animations) as boundary objects in the implementation of a novel agricultural production system in The Netherlands (Klerkx et al., 2012).

Scholars also have often focused on explaining the role of individual boundary elements that mobilized science, policy, and practice in specific innovation processes (in terms of scope or timescale) within broad transformative processes in agri-food sectors (Franks, 2010; Favilli et al., 2015; Clark et al., 2016) – e.g., the contribution of boundary work provided by food labels in the development of organic food production in England (Eden, 2011). Moreover, there are some studies dedicated to analyzing the role played by the interplay between boundary elements in transformative processes (Lamb, 2011; Blades et al., 2016; Betzold, 2018) – e.g., a study from the SOLINSA (Support of Learning and Innovation Networks for Sustainable Agriculture) project identified how different types of boundary work and objects performed together to involve actors in learning and innovation initiatives (Tisenkopfs et al., 2015).

These studies on agri-food system innovation and transformation suggest that boundary elements might perform together to underpin the various collaborative efforts required by transformative processes, and co-evolve with but also shape directionality. This is in line with previous work in the Science and Technology Studies (STS) field that has shown that boundary elements sometimes expand and perform in a connected way to keep coherence across wider scopes of space and time (Star, 2010). Such organized networks of boundary elements have been referred to as *boundary infrastructure* (see Star and Bowker, 2006; Bowker et al., 2009; Tempini, 2015; Dagiral and Peerbaye, 2016). In its limited empirical application so far, the boundary infrastructure concept has helped to analyze under which circumstances individual boundary elements related to digital platforms evolved until becoming a boundary infrastructure, achieving the capacity to steer how researchers, policy-makers, and other actors interact to produce knowledge in themes such as climate change, healthcare, and rare diseases (Dagiral and Peerbaye, 2016; Park, 2010; Tempini, 2015).

This study aims to deepen the understanding of long-term transformative processes in agri-food systems by looking at the role of boundary infrastructures in supporting innovation over time concerning directionality within transitions. Drawing upon the STS literature previously mentioned (Bowker et al., 2009; Star, 2010; Dagiral and Peerbaye, 2016), we posit that boundary infrastructures play a pivotal role in aligning interests and allow for spurring joint action related to how innovation in support of agri-food systems transformation evolves in time and space. Empirically, we analyze the evolution of the Brazilian pig production system (henceforth BPPS) from a setting in which it mainly produced pork lard for a domestic market to a setting of being integrated into global supply chains and following international standards, a long-term transformative process that started in the 1960s. Similar transformations of pig production systems have also taken place elsewhere, for example in The Netherlands (Elzen et al., 2011; Geels, 2009). Empirically, the key question that guides this study is: How did boundary infrastructures influence the evolvement of the long-term transformative process experienced by BPPS from the 1960s to date? By answering this question, we aim to contribute to debates on how interactions between science, policy, and practice promote coordination, manage contingency, shape directionality, and sustain long-term changes in agri-food systems (Chabbi et al., 2017; Nel et al., 2016; Sarkar et al., 2018; Zougmoré et al., 2019; Klerkx and Begemann, 2020). Moreover, an in-depth understanding of boundary infrastructures can inform debates on how to shape the transformation from unsustainable and locked-in agri-food systems (Conti et al., 2021) towards desirable scenarios, such as establishing more sustainable food production systems (e.g., Lamine, 2011; El Bilali, 2018; Ingram, 2015; Gaitán-Cremaschi et al., 2019). We provide insights from a middle-income country, hence also responding to recent calls to contribute more empirical work from such contexts to agri-food transition studies (Hebinck et al., 2021).

The remainder of the paper is structured in five more sections. The conceptual approach is explained in section 2. Section 3 presents the methodology for applying the conceptual approach in the BPPS case. Section 4 presents the analysis and the empirical results of the case study. Section 5 presents a discussion and lessons learned from the Brazilian case, and conclusions are drawn in section 6.

2. Boundary elements

Since the 1980s, constant conceptualization efforts have been made to grasp interactions between science production, policy, and practice actions, and how these influence innovation and transformative processes, in different contexts. In view of the oft found separations between these realms, STS scholars worked with the concept of "boundary" to initially delimit science from non-science (Gieryn, 1983). This concept consequently has been expanded into different directions to make it more operational, and has been applied in diverse fields such as administrative, management and organization science (Nicolini et al., 2012; Sapsed and Salter, 2004; Williams, 2002) and innovation, transition and design studies (Franco-Torres et al., 2020; Klerkx et al., 2012; Smink et al., 2015). In this endeavour, several analytical and conceptual tools have been proposed to explain what enables individuals and organizations with different mandates and interests to work beyond and cross boundaries. This study will use four boundary elements: boundary objects, boundary organizations, boundary spanners, consequently bringing these together in boundary infrastructures.

2.1. Boundary objects

Star and Griesemer (1989) defined boundary objects as elements that link different sets of diverse interests. They are plastic enough to fit into local contexts and the particular interpretation of various parties using them, yet robust enough to provide a shared identity across sites (Star,

[2] For the purposes of this paper, 'science' is the realm where take place intellectual and practical efforts to build systematic approaches to the creation of new knowledge (Wyborn et al. (2017). "The science, policy and practice interface." et al., 2017). In its turn, 'policy' is the realm where legislative, public management, and resource allocation decisions are built by groups with the power to do so (Carr and Wilkinson, 2007). 'Practice' is the realm where the actual application or use of knowledge takes place (Nesshöver et al., 2017).

2010). In general, scholars have categorized boundary objects as artifacts, discourses, and processes, which materialize in reality through tangible and intangible forms – e.g., a mission statement, a website, a scale model, a picture, a database, or an idea (Star, 2010; Wenger, 2010; Metze, 2020; Steger et al., 2018). In innovation and transformation, boundary objects facilitate the alignment of interests and joint action formation, and consequently, previous agri-food innovation studies have identified these boundary objects as elements that perform as 'vehicles for change' (Tisenkopfs, 2015). They play such a role by enabling networks of actors from science, policy, and practice to align around a specific vision, negotiate a shared direction, and enhance collaboration (Klerkx et al., 2012; Theodorakopoulos et al., 2014; Urquiza et al., 2018).

Extant literature has identified particular functions boundary objects play to allow the alignment of interests and joint action formation in change processes (Tisenkopfs, 2015). Boundary objects function as mediation tools to allow communication and knowledge integration between actors from science, policy, and practice (Kimble et al., 2010; Clark et al., 2010; Klerkx et al., 2012). They also exert coordination functions in change processes, as they support negotiation to align actors with diverse, if not contradictory to some extent, interests (Favilli, 2015; Steger et al., 2018). Additionally, boundary objects operationalize joint action formation by creating 'running interfaces' where science, policy, and practice can collaborate under agreed rules (Tisenkopfs, 2015).

2.2. Boundary organizations

Boundary organizations find their habitat at the margins of different professional realms or social worlds, such as policy and science (Guston, 2001; Cash et al., 2003). Their main task is to perform boundary work and enable alliances to build collective knowledge (Miller, 2001; Parker and Crona, 2012). They play this role by facilitating collaboration between scientists and non-scientists and remaining accountable to both (O'Mahony and Bechky, 2008; Cash et al., 2003; Carr and Wilkinson, 2005). Guston (2001) emphasizes that boundary organizations explicitly conduct or study the boundary between science and other realms. In doing that, boundary organizations stabilize the interactions between science, policy, and practice. Successful boundary organizations thus succeed in satisfying the needs of different sorts of actors. For example, a technology transfer office performs boundary work by promoting collaboration between scientists and private companies through invention disclosures (Orsini et al., 2017), which delivers benefits to all (e.g., scientists have societal impact, and companies can develop new products).

Previous studies that applied an expanded understanding of the concept (e.g., beyond the science-policy or science-practice interface) have also identified that boundary organizations act as durable structures in long-term transformative processes that encourage isolated parties to align around their convergent interests to promote innovation (O'Mahony and Bechky, 2008). In this sense, STS scholars have suggested that boundary organizations perform intermediation, in line with ideas from transition studies on the roles of intermediaries in systemic change (Kivimaa et al., 2019a, 2019b). When performing as durable intermediary structures in long-term transformative processes, boundary organizations may play diverse functions. For this study, we synthesize from extant literature three leading roles for boundary organizations in this respect. First, they mediate the interactions between science, policy, and practice by developing an institutionalized arena where organizations and individuals involved in turning knowledge into innovation can negotiate their divergent interests (Cash et al., 2003; Parker and Crona, 2012; Fudge and Hiruy, 2019). Second, they coordinate the construction of boundary objects and often participate in their operationalization (Carr and Wilkinson, 2005; Champenois and Etzkowitz, 2018; Gustafsson and Lidskog, 2018). Third, following ideas on innovation and science funding agencies as boundary organizations, they manage funding allocation (Klerkx and Leeuwis, 2008; Kirchhoff et al., 2015).

2.3. Boundary spanners

In addition to the concepts of boundary objects and organizations, STS studies have increasingly recognized that boundary spanners are critical for socio-technical transformations due to their roles in innovation processes (Carlile, 2004; Long et al., 2013; Ryan & O'Malley, 2016) and broader transitions (Smink et al., 2015). An early boundary spanners definition referred to them as professionals who operate at the periphery or boundary of an organization, linking it to external elements (Carlile, 2004; Bednarek et al., 2018). More recently, scholars have paid attention to how boundary spanners cope with inter-organizational and multi-sector environments where interactions do not focus only on managing the interface between an organization and its environment but actively involve collaboration with external agencies and interests (Williams, 2013; Champenois and Etzkowitz, 2018; Goodrich et al., 2020). From this perspective, boundary spanners are individuals (or groups of them) who work between knowledge producers and users, building boundary tools (such as boundary objects) that enable collaboration, and are accountable to all different groups involved in an innovative process (Parker and Crona, 2012; Safford et al., 2017).

Extant literature has emphasized the role of specific structures set up to develop boundary-spanning activities in innovation processes (Ernst and Chrobot-Mason, 2011; Safford et al., 2017). These structures, named boundary spanner units, can range in size from one individual to an entire section in a private organization, government agency, or non-governmental organization (van Meerkerk and Edelenbos, 2018). They often focus on aligning interests and fostering joint action associated with innovation (Safford et al., 2017). This type of boundary spanner performs roles similarly to boundary organizations. However, the difference is that it is not their primary purpose to furnish boundary-spanning activities (Lundberg, 2013).

Boundary spanners chiefly perform three functions to support innovation: communication, translation, and mediation. Communication builds the ground where different actors will understand one another (Ernst and Chrobot-Mason, 2011). Translation refers to efforts to interpret and make understandable for all actors the different experiences, assumptions, and even language barriers that often hinder mutual comprehension (Safford et al., 2017). In turn, mediation provides a safe arena for negotiation and collaboration (Dekker et al., 2019).

2.4. Boundary infrastructures

STS scholars have also paid attention to how devices, organizations, and other tools that function as boundary elements interact and evolve as time goes by. As mentioned before, they inferred that beyond a certain point, boundary elements might expand, envelop the communities they bind, and become a "boundary infrastructure" (Bowker and Star, 2000; Star and Bowker, 2006; Bowker et al., 2009; Tempini, 2015; Dagiral and Peerbaye, 2016). Bowker and Star (2000) first noted that boundary objects sometimes scale up or become standardized, bringing diverging interpretations and uses into line or making them marginalized. The authors argued that, in such circumstances, boundary elements start performing as infrastructure, "allowing for local variation together with sufficient consistent structure to allow for the full array of bureaucratic tools to be applied" (Bowker and Star, 2000: 313).

The distinction between boundary elements and boundary infrastructures is one of scale but also of perception (Star, 2010). A boundary infrastructure becomes omnipresent, has its use universalized, and operates at a macro-level inside the context that embeds it. It also functions as a naturalized backdrop, a transparent space where interactions between actors from different communities occur as if they are spontaneous (Bowker and Star, 2000). Star (2010) emphasized that boundary infrastructures (i.e., the different boundary elements that scaled up in a specific context), when seen together, function as an organized network focused on "keeping things moving." They provide the material, technical, and social ground that simultaneously serve multiple communities of practice and allow them to build and use shared work practices and information requirements (Star and Ruhleder, 1996; Bowker and Star, 2000).

2.5. Design, dynamics, and tensions in boundary infrastructures

According to STS literature, understanding boundary infrastructures relies on looking at how they evolve and operate (Bowker et al., 2009; Fremont et al., 2019; Orsini et al., 2017; Steger et al., 2018). Complex infrastructures, such as boundary infrastructures, emerge from the interplay between technical and social actions developed by multiple actors within socio-technical systems (Star and Bowker, 2006; Dagiral and Peerbaye, 2016). They present a long-term evolution (their time scale can be decades to centuries) and enhance their explicitness and reliability as they grow. Boundary infrastructures often grow based on incremental maneuvers (change takes into account failures in the previous infrastructure and does not occur not all at once or everywhere simultaneously), and such maneuvers are not always the result of deliberate planning (Star and Ruhleder, 1996; Bowker and Star, 2000; Clark et al., 2016).

Extant work also emphasizes that three aspects are crucial to capture how complex infrastructures operate: design, dynamics, and tensions (Edwards et al., 2007; Bowker et al., 2009; Ribes and Finholt, 2009; Karasti, 2014; Karasti and Blomberg, 2018). Design refers to which boundary elements (objects, organizations, and spanners) compose boundary infrastructures. Dynamics relate to how boundary infrastructures foster or restrain connectedness between elements in their operationalization and evolvement – i.e., to what extent boundary objects, organizations, and spanners work synergically. In turn, tensions refer to power struggles. As boundary infrastructures grow, they create benefits, but there are always losers and winners in infrastructure formation (Edwards et al., 2007). Questions of management, control, and access are always present (e.g., who leads, resolves clashes, and determines the direction of change). In practice, all of them are critical to boundary infrastructures operationalization and evolvement – Fig. 1 shows the conceptual understanding of which elements make up boundary infrastructures and how these complex infrastructures emerge and evolve.

In what follows, we will analyze how boundary infrastructures took part in BPPS evolvement from pork lard to international standards, unravelling three circumstances. One, we will describe which boundary elements operated at a macro-level in the different cycles of BPPS evolution. Two, we will depict how these boundary elements performed together and became a boundary infrastructure, looking at which design, dynamics, and tensions boundary infrastructures developed along with BPPS evolvement. Three, we will see how boundary infrastructures assumed capacities of aligning interests and allowing joint action formation to support innovation over time.

3. Research methods

This study took a qualitative approach based on an exploratory case study design to unravel how boundary infrastructures emerge and evolve and how they play a role in transformative processes, following others who have taken a similar approach to study this topic (Geels and Penna, 2015; Royer et al., 2017; Spiertz and Kropff, 2011; Trifković, 2014). Case studies are suitable to approach phenomena that are not well known, have many facets, and require an in-depth perspective (Eisenhardt and Graebner, 2007; Gray, 2004). Furthermore, a valuable strength of the case study research methodology is that it affords a rich context for answering 'how' and 'why' questions (Yin, 2009).

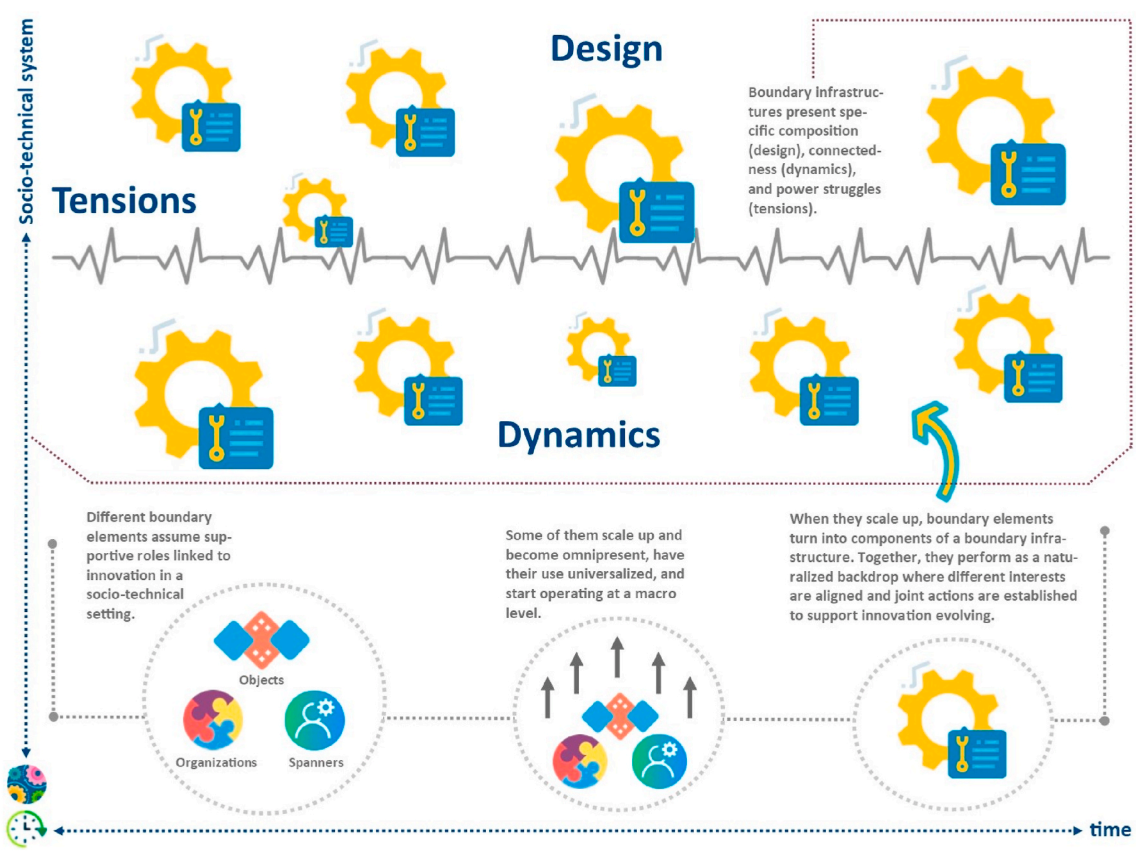

Fig. 1. Conceptual understanding of boundary infrastructures development and operationalization.

The empirical case analyzed in this study comes from the agricultural context in Brazil, referred to variously as a developing or emerging country (since it is high-middle income but with high disparities), where agri-food sectors have undergone remarkable transformative processes in recent decades (Boddey et al., 2003; Brooks, 2017; Chaddad, 2016). We focus on how boundary infrastructure development influenced BPPS to evolve the spot market setting to the international standards setting. Four reasons underpin this choice. First, BPPS has been one of Brazil's most transformative agri-food systems in the last six decades (Chaddad, 2016), evolving from an artisanal and fragmented activity to a well-structured agri-food sector (Talamini et al., 2014). Second, interfaces between science, policy, and practice played an essential role in its development (Guimarães et al., 2017; Sebrae & ABCS, 2016). Third, many people who had critical roles in BPPS development are still available to describe how this sector has evolved. Furthermore, BPPS has reliable databases about its growth in the last 60 years.

The primary data sources for this work were 41 in-depth interviews conducted with influential actors at BPPS, such as representatives from industries, producers, governmental institutions, NGOs, science institutions, and advisory services (see Appendix 1). After mapping crucial players linked to pig production governance (based on previous knowledge about BPPS and additional information collected on websites made available by industries, associations, public organizations, NGOs, and science institutions), this study established a list of 32 interviewees. Nine further interviewees were added via the snowballing method (Kumar, 2011). The interviews, conducted between July and December of 2017, lasted between half an hour and 2 h and were tape-recorded and transcribed verbatim. They followed an interview guide based on our literature review of transformative processes in agri-food sectors and the boundary infrastructure concept. The interview guide focused on: 1) basic information on the BPPS trajectory, 2) which sort of interactions between science, policy, and practice influenced BPPS development, 3) and BPPS general performance and societal impacts over time. Core and additional secondary data were also collected. The core secondary data consisted of books, scientific papers, policy briefs, official public reports, and media articles published in newspapers and magazines. Additional secondary data came from pig industries' official websites and annual reports published by industry and producer associations (see Appendix 2 for core and additional secondary data sources).

Furthermore, we triangulated the interview content with secondary data. As suggested by Yin (2009), analysis of the transcripts and secondary data started during data collection. Thus, we could sharpen later interviews and focus on significant events linked to the BPPS trajectory. The triangulation between interview content and secondary data was interpreted using the theoretical framework as an analytical lens. In terms of possible biases, as regards internal validity, the findings rely on actor representatives in high positions (usually CEOs, researchers, or senior consultants) who were able to provide a broad view of BPPS evolvement and functioning. In terms of external validity, the findings linked to interviews, secondary data, and the interpretation underpinned by the theoretical framework were reviewed by two researchers specialized in BPPS development. They validated the boundary infrastructure evolvement described in the findings section.

4. Findings

We will present the findings in four sub-sections guided by the four major transformation cycles BPPS experienced over time. Firstly, we will briefly describe how those cycles unfolded. Secondly, we will explain how boundary infrastructures emerged and influenced change by aligning interests and allowing joint action formation to support innovation in each of those four major transformation cycles. The findings will be presented in chronological order, as much as possible.

4.1. From pork lard to international standards

Brazilian agriculture went through massive changes from the 1960s to date, making Brazil an acknowledged case of rapid agricultural transformation in a developing country (Ioris, 2017). BPPS took part in this long-term transformative process and underwent consecutive cycles in which the incorporation of technical and organizational innovations provoked profound changes (Talamini et al., 2014). Drawing on previous literature (see Miele et al., 2011; Souza et al., 2011; Sebrae, & ABCS, 2016; Guimaraes et al., 2017), this study identified that the BPPS trajectory experienced four major transformation cycles. Fig. 2 presents a brief description of these four cycles. Next, we will show how boundary infrastructures supported innovation in each of these cycles.

4.2. BPPS's initial boundary infrastructure: alignments and joint actions focused on herd prolificity and carcass quality

BPPS had its socio-technical setting structured around pork lard production since the early 1940s (Spies, 2003; Fávero et al., 2011). In that setting, which remained unchanged until the mid-1960s, producers had pigs for their own consumption and used to sell their production surplus to small regional abattoirs once or twice a year (Sebrae & ABCS, 2016). This socio-technical setting proved proper for raising rustic animals suitable for lard production. Beyond that, it did not demand specific skills from producers (Souza et al., 2011). However, changes in the Brazilian economy and society (such as introducing vegetable oils, domestic refrigerators spreading, and the new Brazilian urban family profile, in which 16.5% of Brazilian women got employed outside their homes) pushed pig production to focus on processed pork products – e.g., sausages, ham (Brito, 2006; Chaddad, 2016). Thus, the setting where rustic animals rich in fat were raised, industrialized, and commercialized became outdated. Gradually from the mid-1960s, the BPPS socio-technical configuration turned its focus to lean meat, an essential raw material for processed pork products (see Fig. 2).

The narratives from the interviews with BPPS representatives revealed that innovation focused chiefly on improving herd prolificity and carcass quality in the period when the shift from pork lard to lean meat took place. Boundary work targeted to support those innovative efforts came from two different types of boundary elements. University researchers (especially from the Federal University of Rio Grande do Sul)[3] operated as boundary spanners by translating foreign knowledge and mediating its local application through initiatives such as technicians' capacitation, technical publications, and producers' organization. Producer associations in Santa Catarina, Rio Grande do Sul, and São Paulo states, where BPPS concentrated at the time, also played a role as boundary spanners. They fostered innovation by 1) mediating the construction of local pig development projects and 2) communicating novelties related to improving herd prolificity and carcass quality by promoting national and state pig fairs.

In their turn, local pig development projects established interfaces where science (universities and independent consultants), policy (the Ministry of Agriculture, state agriculture departments, and policymakers), and practice (producers associations and pig genetics producers) started working together to set up an articulated pig genetic improvement process. Those local projects scaled up to another level from the late 1960s to the mid-1970s. From this basis, the state pig genetic improvement programmes emerged, which became pieces of the original boundary infrastructure in BPPS. State programmes, implemented in Santa Catarina, Rio Grande do Sul, and São Paulo states,

[3] The most acknowledged 'spanner' among university researchers was Luiz Carlos Pinheiro Machado. He published The pigs in 1967, the most influential technical book in BPPS at the time. Additionally, he helped found the Brazilian Pig Producer Association in the late 1950s and chaired it between 1963 and 1964.

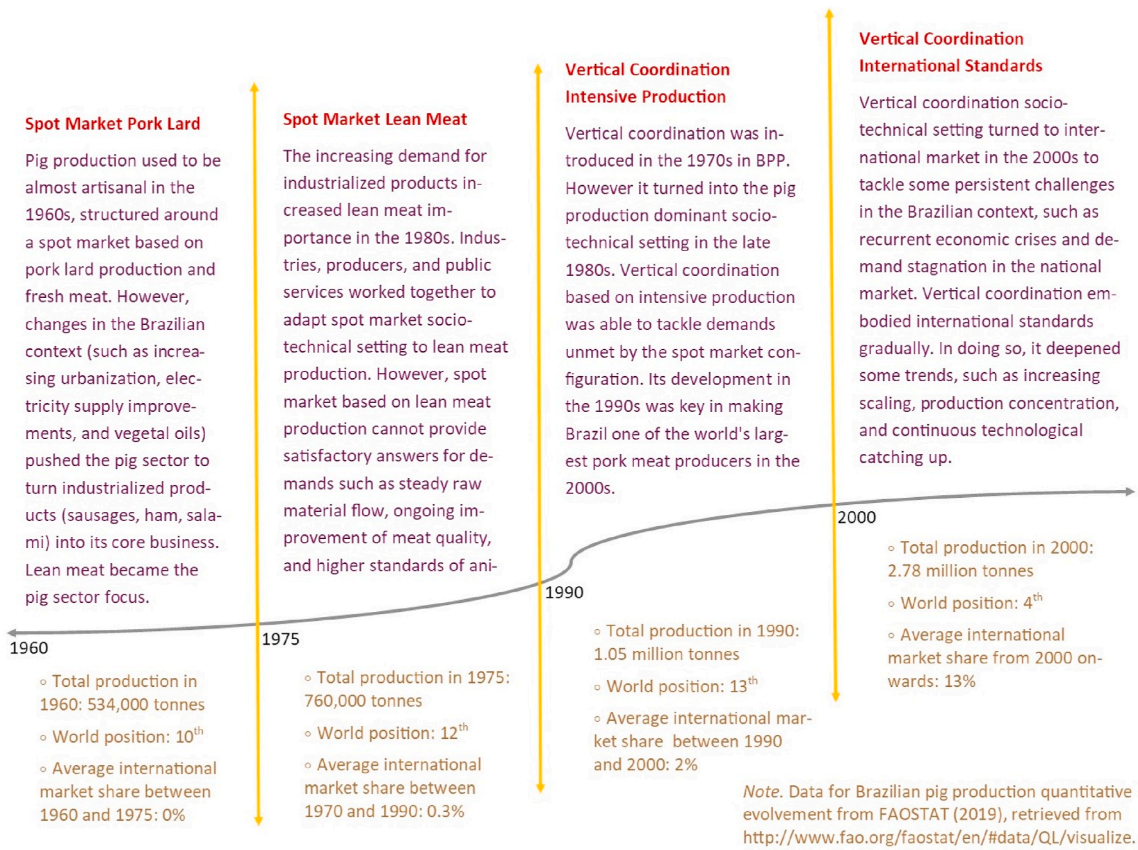

Fig. 2. Brief overview of transformation cycles that BPPS underwent from the early 1960s to date.

turned into a boundary infrastructure for two reasons. First, they operated at a macro-level within BPPS, aligning interests and promoting joint actions between actors from the different regions focused on pig production. Second, they started functioning as the original naturalized backdrop where science, policy, and practice interacted to set up agreed working relationships related to the pig genetic improvement process.

This first design of the boundary infrastructure linked to innovation in BPPS presented a simple configuration made up of few elements. However, its pieces performed in a highly connected way. Since all the state pig genetic improvement programmes contributed to similar aims, they worked synergically, sharing information and funding. Such dynamics functioned as a crucial support to innovation related to improving herd prolificity and carcass quality. Table 1 presents how the boundary infrastructure in the pork lard setting performed to support innovation.

However, the BPPS boundary infrastructure also experienced some tensions during the shift from pork lard to lean meat. Science actors (university researchers mainly) advocated supporting innovation beyond pig genetics improvement, covering animal management, animal health, and meat industrialization. There was no prospect that those demands could be fulfilled by the state pig genetic improvement programmes. Moreover, practice actors built up additional interests as time went by. Pig producer associations led the boundary infrastructure at the time, which primarily benefited pig genetic material producers' interests. Other practice actors, such as industries and pig raw material producers, did not see their concerns fully met in the boundary infrastructure design and dynamics at that time. The following quote illustrates the tensions described above:

> I believe that the state programmes delivered what they initially proposed. However, pig production was changing quickly, and not all forces that built them believed that sort of arrangement could handle the demands that were coming. *(A former pig researcher, who took part in the state pig genetic improvement programmes)*

Table 1
Boundary infrastructure, alignments, joint actions, and innovation in the pork lard setting.

Boundary infrastructure components	Functions played	Interests aligned	Joint actions intermediated	Crucial related innovations
• State pig genetic improvement programmes	• Knowledge integration • Enabler of collaboration	• University researchers • Pig genetics producers • Public organizations • Policy-makers	• Development of zootechnical tests of imported pig genetic materials • Implementation of feeding experiments adapted to Brazilian conditions • Development of databases on zootechnical and feeding performance of genetically improved pigs • Importation of improved genetic material from Europe and the United States	• Brazilian pig genealogical record service • Publication of the nutrient requirements of Brazilian pigs • Genetic improvements of pure breeds (such as Duroc, Wessex, Hampshire, Berkshire) adapted to the Brazilian context • Introduction of new pure breed pigs focused on lean meat (Landrace, Large White, Piétrain)

4.3. The boundary infrastructure broadens its design to adapt imported knowledge and technology in the lean meat setting

After finishing the shift from pork lard to lean meat, BPPS assumed a broader and more complex socio-technical configuration in the early 1980s. Industries with a national scope replaced the small regional abattoirs that headed pig production in the pork lard setting. The pig sector also started demanding producers' professionalization (Bosísio et al., 2003; Brito, 2006). BPPS representatives interviewed in our fieldwork research emphasized that innovation focused on production intensification by adapting imported knowledge and technologies related to pig health, pig husbandry, genetics, and meat industrialization to the Brazilian context.

Boundary work targeted to support innovation broadened its interests and focus, resulting in the emergence of new boundary elements. One of these new boundary elements was the National Pig Research Centre, deployed by the Ministry of Agriculture. The Brazilian government set it up due to the mobilization of industries, producers, policymakers, and scientists to establish an institution committed to innovation demands from the pig sector. Thus, the National Pig Research Centre took up an official mandate as a boundary organization dedicated to mediating, coordinating, and funding efforts to promote innovation in BPPS.

The National Centre's emergence was also connected directly to the building of a new boundary object. As one of its first tasks, the National Pig Research Centre constructed and operated the National Pig Research Programme. It functioned similarly to what has been referred to elsewhere as an innovation platform (see Kilelu et al., 2013) until 1992, coordinating and funding basic research and innovation in BPPS. Beyond this practical function, it also had a significant symbolic function (hence it could be considered as a boundary object), and The National Pig Research Programme became a crucial interface to align groups with different interests (such as the Ministry of Agriculture, state departments of agriculture, universities, industries, producers, and suppliers) and spur joint action.

Another boundary element emerged when two of the four biggest Brazilian pig companies in the 1980s[4] started developing the vertical integration model, named the "integration system" in Brazil.[5] Sadia and Seara set up departments specialized in innovation and technology transfer (henceforth ITTDs) to back up implementing that new production model, which focused on regulating raw material flow and quality (Sebrae & ABCS, 2016). ITTDs functioned as boundary spanners by enabling communication and mediating how suppliers, consultants, university researchers, research institutions, and public organizations worked together to solve issues related to "integration system" implementation in those Brazilian pig companies. However, ITDDs did not scale up to the 'full' boundary infrastructure while BPPS was in the lean meat socio-technical configuration. They kept their influence restricted to working with the pig companies that first implemented them and not all companies, functioning in the early 1990s as an experimental boundary spanner between science, policy, and practice actors for the companies involved (Sadia and Seara).

A last boundary element within the boundary infrastructure in the lean meat setting in BPPS grew on the installed base built in the pork lard setting. The state pig genetic improvement programmes were extended to Minas Gerais and Paraná, adding to the previous initiatives in Santa Catarina, Rio Grande do Sul, and São Paulo. They performed as five connected structures to coordinate, promote knowledge integration, and enable collaboration to support innovation related to pig genetics improvement, in addition to the National Pig Research Centre and the National Pig Research Programme. The latter two at a national macro-level and became two essential pieces in the lean meat configuration.

Boundary infrastructure dynamics in the lean meat setting showed even sharper synergy between elements that made it up. Such dynamics had to do with how the National Pig Research Centre and the National Pig Research Programme biased and funded the alignment of interests and joint actions formation. Table 2 summarizes how boundary infrastructure in the lean meat setting supported innovation.

Nonetheless, significant tensions came up when Brazil's cyclical economic crisis affected the National Pig Research Centre's capacity for supporting boundary elements through the National Pig Research Programme – both relied on public resources, which decreased notably in the late 1980s and early 1990s (Souza et al., 2011). The following quote of a former industry executive illustrates another tension related to the BPPS boundary infrastructure:

> We acknowledge that innovation and development based on the National Pig Research Centre leadership brought many improvements to Brazilian pig production. However, in the 1980s, Brazilian pig production began to export carcasses to Europe, and we needed to go forward quicker in terms of animal health, animal feeding, and management. […] It turns out that we realized that the way we used to foster innovation would not be enough to follow the international market standards. *(A former industry executive who headed private research and advisory services in the 1980s and took part in The National Pig Research Programme)*

4.4. Vertical coordination: public and private leverages drive the boundary infrastructure

Although displaying acknowledged improvements (in the view of respondents) compared to the pork lard setting, the lean meat setting failed to cope with the modernization of pig slaughtering production lines, which started demanding standardized carcasses in terms of length and thickness of bacon in the late 1980s (Fávero et al., 2011). Furthermore, the lean meat setting could not ensure a steady raw material flow (Talamini et al., 2014). Those shortcomings took the four biggest Brazilian pig companies to implement the vertical coordination model in their whole production system. That decision spread the vertical coordination model within BPPS, which became hegemonic in the early 2000s. For example, pig production underpinned by vertical coordination went from less than 15% of overall production in 1990 (Souza et al., 2011) to 33% in 1994 (Nicolau et al., 2001), 42% in 1997 (Martinelli, 2009), 50.5% in 2000 (ABPA, 2000), and 83% in 2017 (Martins et al., 2017).

The narratives from the interviews with BPPS representatives showed that the vertical coordination setting directed innovation to deepen the change process initiated in the lean meat setting to produce pig meat in the quantity and quality required by the rapid expansion of pig production – Fig. 2 shows that Brazil went from the 13th to the 4th largest world producer in one decade. Chiefly, boundary work in the vertical coordination setting aimed to enable further technological improvements in pig health, pig husbandry, feeding, genetics, pig meat production methods, and pig meat industrialization processes, all

[4] Sadia, Perdigão, Aurora, and Seara were the largest Brazilian pork industries in the 1980s and 1990s (Nicolau et al., 2001). In 1995, they accounted for more than 40% of Brazilian production. All of them started in Santa Catarina state, but from the beginning of the 1980s, they led the first round of a concentration process of pig meat industrialization in Brazil (ABCS, 2014).

[5] Pig production is governed by a contract between pig processing industries and pig producers in the integration system. The contractor, commonly an industry, coordinates production operations vertically. Generally, the producer makes available facilities where pigs are raised and whose features must meet the integrator's standards, besides providing his own or contracted labour. In turn, industries provide pigs, animal feeding, and advisory services to rural properties. Each integration system adapts itself to the context in which the industry and its associated producers embed, but in general, all have the following items: contracts between producers and industries, own advisory service, and strict technological packages (Miele et al., 2011; Sebrae & ABCS, 2016; Spies, 2003).

Table 2
Boundary infrastructure, alignments, joint actions, and innovation in the lean meat setting.

Boundary infrastructure components	Functions played	Interests aligned	Joint actions intermediated	Crucial related innovations
• State pig genetic improvement programmes • Pig National Research Centre • National Pig Research Programme	• Joint actions coordination and operation • Joint actions funding • Knowledge integration • Collaboration enabler	• National pig industries • Pig meat producers • Pig genetics producers • Public organizations • Policy-makers • Research institutions • Universities	• Cooperation to study pathogens affecting Brazilian pig production • Development of national vaccines • Cooperation to study alternative feed for pigs, nutrients digestibility, feed additives, and grain milling efficiency • Description of genetics characteristics of the Brazilian pig herd • Development of artificial insemination techniques adapted to the Brazilian context • Development of equipment and facilities for intensive production adapted to the Brazilian climate	• Vaccine protocols adapted to the Brazilian context • Atrophic rhinitis vaccine • Pig Information System (SIS Suínos) • Pyramid breeding system for pig genetics improvement • Pig carcass grading system • Pig semen freezing technique adapted to the Brazilian context • Technological packages for handling piglets, sows, and finishing pigs adapted to the Brazilian context • Animal feeding protocols adapted to the Brazilian context

related to pig production intensification.

ITTDs carried on performing as boundary spanners in the vertical coordination setting. They proved to be more efficient than other previous boundary elements (such as state pig genetic improvement programmes and the Pig National Research Centre) to fulfil vertical coordination demands. Together, ITTDs linked to the largest pig industries led the mobilization of suppliers, university researchers, research institutions, and public organizations to develop or adapt technological solutions to boost production intensification. Beyond ITTDs, boundary work to support vertical coordination was also done by the National Pig Research Centre. Although not playing a pivotal role in mediating, coordinating, and funding initiatives to support innovation, the National Pig Centre kept its role as a boundary organization. Another boundary element was the Public Pig Genetics Improvement Programme (boundary object), which replaced the state programs to coordinate and mediate hybrid pigs development for producers not associated with pig industries.

The spreading of the vertical coordination model allowed that ITTDs scaled up and became part of the whole BPPS boundary infrastructure. The National Pig Research Centre and the Public Pig Genetics Improvement Programme continued to work at the macro-level and stayed part of the boundary infrastructure, thus contributing to its design and composition. The boundary infrastructure in this setting also presented a different connectedness between its components because of vertical coordination. The National Pig Research Centre and the Public Pig Genetics Improvement Programme developed a high synergy as they followed public interests in promoting innovation related to production intensification. ITTDs mainly followed private interests and connected to the other two boundary infrastructure components only when this was aligned to pig industries' concerns. For example, ITTDs and the National Pig Research Centre combined efforts to align interests and promote joint actions related to various production intensification issues, such as pig producers' professionalization and pig meat safety and quality. Nevertheless, they showed low synergy with the Public Pig Genetics Improvement Programme as each pig industry preferred to stimulate alignments and joint actions linked to its own pig genetics programme. Table 3 synthesizes contributions to innovation provided by the design and dynamics boundary infrastructure adopted in the vertical coordination setting.

The boundary infrastructure also experienced unprecedented tensions through the 1990s and early 2000s. For the first time, there were some disjointed standpoints between public and private interests within BPPS boundary infrastructure. Private interests pushed boundary infrastructure components to focus only on production intensification. On the other hand, from the late 1990s, societal mobilization (led by non-governmental organizations, university researchers, public organizations, research institutions) started advocating that boundary infrastructure components following public interests (such as the National Pig Research Centre) should also align interests and promote joint actions to tackle production intensification side effects (e.g., environmental issues, pig diseases dissemination, and production intensification exclusions). The following quote of an advisory service consultant explains further tensions between public and private standpoints:

> Pig industries took on the pig production technological development in the 1990s and created effective structures where science institutions, suppliers, producers, and public and private organizations interacted to increase pig meat production and industrialization. At first, demands that did not fit this purpose were disregarded. However, some societal claims started claiming that unbalances provoked

Table 3
Boundary infrastructure, alignments, joint actions, and innovation in the vertical coordination setting.

Boundary infrastructure components	Functions played	Interests aligned	Joint actions intermediated	Crucial related innovations
• Pig Industry Innovation and Technology Transfer Departments (ITTDs) • Pig National Research Centre • Public Pig Genetics Improvement Programme	• Coordination and operation of joint actions • Funding of joint actions • Knowledge integration • Enabler of collaboration • Facilitator of communication	• National pig industries • Pig meat producers • Public organizations • Policy-makers • Research institutions • Universities • Suppliers	• Cooperation to further study pathogens affecting Brazilian pig production • Cooperation to study pathogens related to pig meat safety and quality • Development and testing related to production methods • Further studies on alternative feed for pigs, nutrients digestibility, and feed additives • Alliances to develop new genetics improvement methods • Alliances to promote pig producer's professionalization • Further studies on equipment and facilities for intensive production adapted to the Brazilian climate	• New pig vaccine protocols adapted to the Brazilian context • New pig husbandry and pig slaughtering protocols • Private advisory services • Hybrid pigs (boars and sows) • Pig husbandry based on three specific production phases (breeding, weaning, and growing-finishing) • New pig feeding protocols adapted to the Brazilian context

by production intensification should also be tackled by who was intermediating innovation at BPPS. *(A pig production advisory service consultant who has worked associated with ITTDs since the 1990s)*

4.5. Boundary infrastructure in the international standards setting: attention also to side effects of production intensification

The vertical coordination setting became increasingly oriented towards international standards from the mid-2000s. In practice, this meant that standards imposed by international buyers gradually turned into crucial transformation drivers in Brazil (i.e., Brazilian industries started pursuing international protocols linked to animal health, animal feeding, animal welfare, environment, traceability, and pig meat industrialization processes). Moreover, BPPS adopted a commoditization strategy, which influenced an unprecedented production scale increasing. Consequently, pig production became more concentrated in fewer pig producers and industries, but those had an international scope (Sebrae & ABCS, 2016). Additionally, awareness and criticism of production intensification side effects gained more ground. Two new topics provoked hot debates on BPPS: 1) animal welfare nonconformities (Dias et al., 2018) and 2) queries on whether the vertical coordination model was economically and socially fair (Schmidt, 2017).

Those circumstances took BPPS to experience some diversification and regulation of the vertical coordination model. Independent pig producers, not associated with industries and accounting for approximately 10% of Brazilian pig meat production (Sebrae & ABCS, 2016), felt excluded and developed their own production organization model based on the vertical coordination concept, the so-called 'mini-integration system'. Moreover, after seven years of debates, the Brazilian National Congress issued the Integration Law in May 2016. It introduced regulations to mediate the relationship between industries and producers inside the vertical coordination model. Among these regulations was the establishment of two mandatory and connected committees. The first is the National Forum for Poultry and Pig Agroindustry Integration (FONIAGRO), responsible for defining the general guidelines that guarantee an improved relationship between industries, producers, and suppliers. The second is the Integration Monitoring, Development, and Conciliation Commission (CADEC), which operates where production contracts regulate partnerships between industries and producers.

The narratives from the interviews with BPPS representatives unveiled that innovation primarily focused on production intensification through international standards implementation. Nonetheless, it also started to tackle the side effects of pig production intensification. Boundary work aimed to support innovation became more diversified to handle those two foci. Accordingly, new boundary elements arose and were added to the ones that came from the vertical coordination setting. The most significant change related to boundary work was introducing boundary elements dedicated to reconciling the different interests at stake regarding production intensification side effects. FONIAGRO/CADECs played a role as a boundary object as they created a dedicated national interface to mediate and coordinate the establishment of alignments and joint actions between the various actors representing science, policy, and practice. Furthermore, private consultants (advisory service companies and independent researchers) have functioned as boundary spanners within the mini-integration system by mediating and coordinating innovation support.

The boundary infrastructure thus adjusted to the international standards settings by adding the FONIAGRO/CADECs to its previous design and configuration, but the private consultants did not achieve a similar macro-level scope at the 'full boundary infrastructure' level, as they played a role as boundary spanners only regarding the mini-integration system. In the international standards setting, the boundary infrastructure dynamics evolved differently than in previous sections. The main difference was that the boundary infrastructure elements had distinct foci, whereas before all of them followed the same guidance - e.g., adaptation of imported knowledge and technology to the Brazilian context (the lean meat setting), production intensification (the vertical coordination setting). For instance, the boundary infrastructure elements driven by private interests (i.e., ITTDs) deepened their focus on supporting innovation related to production intensification. Boundary infrastructure components following public interests (such as the National Pig Research Centre) turned to tackle production intensification side effects primarily.

Those distinct foci did not inhibit connectedness since boundary infrastructure elements under public guidance also took part in boundary work actions related to production intensification, as ITDDs connected to the National Research Centre, the Public Pig Genetics Improvement Programme, and FONIAGRO/CADECs to mitigate undesirable consequences of pig production. As a result, innovation in BPPS went beyond production intensification, as Table 4 demonstrates. The most significant changes added to BPPS socio-technical setting recently have to do with mitigating pig production side effects, such as environmental impact, animal welfare issues, and economic and public health threats linked to diseases.

Accordingly, tensions within the BPPS boundary infrastructure decreased again in the evolving design. Despite initially having different foci, public and private interests were connected as the boundary infrastructure elements simultaneously addressed production intensification and its side effects. Additionally, ONIAGRO/CADECs have played an essential role in relieving tensions within boundary infrastructure, as they provided institutionalized interfaces to bridge differences and build agreed understandings on pig production evolvement. The following quote illustrates this:

> I believe that the FONIAGRO/CADECs can successfully intermediate to tackle the adverse effects that progress sometimes brings to specific segments in Brazilian pig production. I believe that they can also bring public and private interests closer in the medium and long term. *(A federal deputy who took part in the multilateral group that established the Integration Law)*

5. Discussion

Through the application of boundary work concepts from the field of Science and Technology studies (STS) in this study, we looked at how collections of boundary elements influenced and orchestrated a long-term transformative process in an agri-food sector. In this section, we reflect on the theoretical and practical implications of our findings. Specifically, we add to the extant literature on how interactions between science, policy, and practice promote coordination, manage contingency, shape directionality, and sustain long-term changes in agri-food systems (Chabbi et al., 2017; Nel et al., 2016; Sarkar et al., 2018; Zougmoré et al., 2019; Klerkx and Begemann, 2020) by highlighting that boundary infrastructures emerged from and in turn structured the long-term transformative process experienced by BPPS. Boundary infrastructures also facilitated multiple science-policy-practice interactions, which legitimized particular visions and values and assigned responsibility and accountability to actors to spur various joint actions supporting innovation. This has implications for how directionality in transitions is shaped. Additionally, this study unveiled that boundary infrastructures evolution in BPPS was incremental, long-term, multi-site, and with intertwined leverage.

5.1. Boundary infrastructures provide interfaces that support legitimization, responsibility, and accountability in long-term transformations

The findings indicate that the BPPS evolution from a setting in which it mainly produced pork lard for a domestic market to a setting of being integrated into global supply chains and following international

Table 4
Boundary infrastructure, alignments, joint actions, and innovation in the international standards setting.

Boundary infrastructure components	Interests aligned	Functions played	Joint actions intermediated	Crucial related innovations
• Pig Industry Innovation and Technology Transfer Departments (ITTDs) • Pig National Research Centre • Public Pig Genetics Improvement Programme • FONIAGRO/CADECs	• National pig industries • Pig meat producers • Public organizations • Policy-makers • Research institutions • Universities • Suppliers • Non-governmental organizations	• Coordination and operation of joint actions • Funding of joint actions • Knowledge integration • Enabler of collaboration • Mediation of interests	• Alliances for pig diseases eradication • Alliances for environmental impact mitigation • Cooperation for animal welfare regulation and implementation • Traceability methods adaptation to the Brazilian context • Alliances to update regulations and methods related to pig meat safety and quality • Alliances to deepen pig producers' specialization • Cooperation to test and adapt imported technologies related to automation in the Brazilian pig facilities	• National disease eradication programmes (Foot-and-mouth disease and Aujezsky disease) • Introduction of new technologies related to pig manure treatment (biodigester systems, manure composting machines, bacteria to speed up manure decomposition, water management methods) • Introduction of new animal welfare procedures and equipment related to pig husbandry (minimum width between joists on slatted floors, rest areas, accommodation of pregnant sows in groups) • Pig meat traceability systems • Computer-controlled information, management, and feeding systems

standards unfolded as a long-term transformative process that encompassed multiple actors, a wide roll of subjects, and different scopes in terms of time and space. Boundary infrastructures supported the evolvement of this transition by facilitating several science-policy-practice interactions to manage all those variables to enable innovation and change. In practice, the boundary infrastructures supported change in the BPPS long-term transformative process by 1) legitimizing particular visions and values related to innovation and aligning science, policy, and practice actors with them, and 2) assigning responsibility and accountability to actors to spur various joint actions in support of innovation.

This support is not neutral but has a certain normativity and directionality and includes certain pathways while excluding others (in line with ideas of Stirling, 2011; Klerkx and Begemann, 2020). Boundary infrastructures legitimized visions and values related to innovation by underpinning specific development pathways and leaving others aside. For example, boundary infrastructures such as the Pig National Research Centre, the National Pig Research Programme, and ITTDs were pivotal to position production intensification as the hegemonic direction in the lean meat and the vertical coordination setting and drove innovation to that direction. Without those infrastructures to legitimize new ideas about progress related to the food sector, it is unlikely that BPPS had replaced the socio-technical setting structured around pork lard production, which had stayed unchanged from the early 1940s until the mid-1970s. On the other hand, the Pig National Research Centre and FONIAGRO/CADECs reverberated societal mobilizations against production intensification side effects in the international standards setting. Thus, they legitimized alternative visions and values for innovation direction that emerged in the mid-2000s, such as pig production sustainable development and social inclusion, which confirms ideas that directionality is constantly negotiated (Pel et al., 2020).

Moreover, boundary infrastructures worked to align science, policy, and practice to support directionality, enacting the legitimized visions and values related to innovation in BPPS. They played this role by operating the innovation agenda that materialized the hegemonic understanding of the development pathway that BPPS should pursue. For instance, boundary infrastructures such as the National Pig Research Programme coordinated and funded initiatives to adapt pig feeding, vaccines, pig genetics, equipment, and facilities to the Brazilian context in the 1980s and 1990s, where the innovation agenda aligned with the production intensification pathway. Besides that, boundary infrastructures (ITTDs and the National Pig Research Centre) led the mobilization to develop or adapt technological solutions to boost production intensification from the 2000s onwards, which resulted in innovations as new pig husbandry and pig slaughtering protocols, hybrid pigs, and pig husbandry based on three specific production phases (breeding, weaning, and growing-finishing).

Boundary infrastructures thus influenced the long-term transformation process experienced by BPPS by assigning responsibility and accountability to actors and organizations to spur various joint actions in support of innovation. Establishing a space where science-policy-practice interactions can address all variables involved in enabling innovation and change was decisive for BPPS long-term transformation, in line with earlier work of others already alluded to interactions between boundary elements (Tisenkopfs et al., 2015; Betzold et al., 2018). This is because individual science, policy, and practice actors often feel uncomfortable at any level to relate to in the field of one or the other due to their frequently different points of view and interests (Gieryn, 1983; Tisenkopfs et al., 2015; Sarkki et al., 2019). The emergence and growth of boundary infrastructures provided the shared space where actors from science, policy, and practice could work together at the macro-level to build innovative solutions to tackle the challenges imposed by the transformation cycles experienced by BPPS from the 1960s to date, and inducing change at the micro-level. Such mobilization became crucial to bring local and regional innovations to a broader context (national level), deal with diverse issues at the same time (such as environmental impact, animal welfare issues, disease eradication, equipment development, the introduction of new pig meat industrialization processes), and operate change for a long-term horizon.

5.2. Boundary infrastructure unfolding in the BPPS trajectory: incremental, long-term, multi-site, and with intertwined leverage

As described above, the long-term transformation experienced by BPPS from the 1960s to date also relied on a structuration process that not only enabled to cross boundaries, but perhaps paradoxically also to identify an even set up boundaries to promote science-policy-practice interactions at the macro-level, which influenced to a large extent how innovation unfolded. Hence, we can see that the boundary infrastructure provided structuration to the evolving transition and emerging new socio-technical system configurations in subsequent settings of the BPPS, and that in turn this evolving setting (re)structured the boundary infrastructures. We will now discuss three main insights taken from this 'dual structuration' process analyzed in the Brazilian case: 1) it grew incrementally, 2) it took time and did not happen all at once or at a single site, and 3) it intertwined public and private leverage.

First, after a starting point, the boundary infrastructures did not grow de novo. They added or replaced boundary elements, but the previously installed base was not dismantled. For example, in the 1990s, ITTDs emerged and became a crucial boundary element to align interests and spur joint actions to support innovation. However, previous boundary elements operating at the macro-level, such as the National Pig Research

Centre and the Public Genetic Programme, remained attached to BPPS boundary infrastructure – i.e., the BPPS boundary infrastructures assumed new configurations over time, but not radically changing from what they had been before. Hence, a boundary infrastructure has an overall fluidity and flexibility, much alike its elements (e.g., boundary objects).

Second, as boundary infrastructures pursued to bridge boundaries for science-policy-practice interactions at the macro-level, this connected to and was fed by different spheres (public, private), domains (organizational, technical, regulative), and subjects (animal health, genetics, animal welfare) at a micro-level (as already alluded to in section 5.1), and vice versa. This was however a mutual structuration process that was itself not fully structured but evolved in a self-organizing fashion, and this correlates what previous STS literature has referred to complex infrastructures construction, which takes place as a long-term evolvement and grows based on incremental maneuvers (Star and Ruhleder, 1996; Bowker and Star, 2000; Clark et al., 2016).

Third, boundary infrastructures evolvement in BPPS experienced intertwined public and private leverage. Public leverage played a pivotal role in driving the building of structures where large-scale science-policy-practice interactions took place initially. In the 1960s and 1970s, boundary elements were added to BPPS boundary infrastructure predominantly through public policies to foster pig genetics improvement. In the 1980s and 1990s, based on the Pig National Research Centre funding capacity, public efforts kept leveraging the building of new boundary elements (such as the state pig genetics programmes).

However, in the 2000s, when demands became more complex, private leverage also started influencing the building of crucial pieces of the boundary infrastructure, especially those related to production intensification (e.g., ITTDs). Public leverage then shifted its attention primarily to turning boundary infrastructures to tackle side effects provoked by production intensification – e.g., the National Pig Research Centre and FONIAGRO/CADECs became the pivotal macro-level interfaces focused on mitigating pig production undesirable consequences. Despite their specific concerns regarding BPPS boundary infrastructures, public and private leverage did not struggle with each other. They have evolved as complementary in the Brazilian case, and thus this study argues that boundary infrastructures evolvement in BPPS experienced intertwined public and private leverage over time. This connects to ideas on how innovation platforms support what has been called ‘co-evolution of innovation’ (i.e. aligning technological, organizational and social innovations) and orchestrate public and private parties (Kilelu et al., 2013; Turner et al., 2020), but the boundary infrastructure shows this is a continuous process which extends far beyond the project lifespans in which innovation platforms typically operate and also at higher levels of system aggregation. This is an added value of the boundary infrastructure perspective.

6. Conclusion

This study uncovered that the long-term transformative process that BPPS have undergone from the 1960s to date counted with evolving boundary infrastructures to enable science-policy-practice interactions at the macro-level, which impacted system change over time. Beyond shedding light on the evolving boundary infrastructure and how it influenced BPPS evolution, our study deepens the understanding of how coordination unfolds throughout long-term transformative processes, a high-interest subject for debates on promoting transformation towards desirable scenarios in agri-food systems. We argue that the building of boundary infrastructures where science-policy-practice interactions occur can be seen as an orchestration mechanism to drive the direction of innovation.

The evolving boundary infrastructure served as an orchestration mechanism because it provided the interfaces to foster science-policy-practice interactions and all kinds of connected innovation support entities (organizations, projects, partnerships, funding) to enact particular innovation pathways throughout BPPS evolving while leaving aside other ones. In practice, the boundary infrastructure orchestrated socio-technical innovation by legitimizing specific visions and values, providing interfaces for negotiation, regulating the relationship between actors with different interests, and distributing funding to enable collaborative initiatives. This also shows that there also needs to be awareness about power dynamics (following Turner et al., 2020; Rossi et al., 2019) in hegemonic boundary infrastructures, which may cause lock-in and exclusion (Clapp, 2021; Conti et al., 2021), and that this also requires being sensitive to diversity in food system transition pathways (Stirling, 2011; Klerkx and Begemann, 2020). This may imply changing boundary infrastructures purposefully by changing boundary elements or create a parallel boundary infrastructure to address other directionalities, which may even require deliberate phase-out of certain elements (van Oers et al., 2021).

Hence, although this study did not look explicitly at sustainability transitions (though environmental and social sustainability and animal welfare concerns have also emerged in BPPS), we believe that these insights may be helpful to the sustainability transitions in agri-food systems literature that, for example, has adopted the multi-level perspective (e.g., Lamine, 2011; El Bilali, 2018; Ingram, 2015; Gaitán-Cremaschi et al., 2019). The perspective enables analysis of whether different boundary elements are present or absent from orchestrating different components of transitions (e.g., technical change, social change, market change). The boundary infrastructure concept is in this way similar to what has been called an ‘ecology of intermediaries’ (Kivimaa et al., 2019a), but adding to this the role of boundary objects, acknowledging the roles of non-human agency in transitions (Contesse et al., 2021; Kok et al., 2021). It also enables a long-term perspective that is sensitive to the evolution of boundary elements (see also Kivimaa et al., 2019 b; van Lente et al., 2020), which is particularly relevant in view of that agri-food systems (in connection with other systems) would require fundamental ‘deep transitions’ (Conti et al., 2021; Schot and Kanger, 2018). This type of study may also be helpful to look at the broader political dynamics, as highlighting the interactions between science, policy, and practice actors in boundary infrastructures can provide insights into the dynamics of inclusion and exclusion in sector transformation, an issue often neglected in studies of agricultural innovation (Pigford et al., 2018).

As our empirical study focused on a single case and was exploratory, and given that the boundary infrastructure concept has not yet been applied in agri-food settings, there are limitations regarding generalizability. We focused on boundary infrastructures linked to the science, policy, and practice interplay within a particular agri-food system in a specific context of pig production. We cannot ascertain that boundary infrastructures function similarly in broader food systems or other socio-technical systems (e.g., education, health, economy), and this would require further studies in other agri-food systems and beyond. For example, whereas this study has focused on an industrialized pig production system, it would be interesting to investigate boundary infrastructures from an agroecology point of view where such learning and innovation structures have also been noted (Anderson et al., 2019; Iyabano et al., 2021; Pant, 2014), also studying whether and how different boundary infrastructures connected to different sorts of food systems interact. Future work would also need to substantiate our findings regarding boundary infrastructure design and its dynamics and tensions. For example, it could deepen on how tensions influence how public and private interests articulate boundary work in long-term transformation processes, and whether certain interaction patterns of public and private actors enable or disable certain directionalities.

Funding

This research was supported by a PhD studies grant for the first author from Embrapa.

Author contributions

Jean Vilas-Boas: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft.: **Laurens Klerkx:** Supervision, Conceptualization, Writing – review & editing.: **Rico Lie:** Supervision, Writing – review & editing.

Acknowledgments

The authors thank the anonymous reviewers for their insightful comments and critiques which were very helful in improving the paper.

Appendix 1

List of interviewees, 2017

Groups of influential actors	Interviewees	Position/Expertise	Total
Industries	BRF SA representative	sustainability, process management	
	BRF SA representative	innovation, start-ups	
	Aurora Alimentos Central Cooperative representative	president	
	JBS Foods	corporate director of livestock	
	Pamplona Food SA	president	
	Frimesa Central Cooperative	executive director	
	Master Agriculture and Livestock	executive director	
	Sadia SA	former executive director	
	Perdigão SA	former executive director	
	Seara Alimentos	former executive director	
	Pig Production Industries Association	president	11
Producers	Brazilian Pig Producer Association	executive director	
	One the biggest Brazilian pig producers	pig producer	
	Santa Catarina Pig Producer Association	former president	3
Advisory services	BRF SA representative	executive director	
	Aurora Alimentos Central Cooperative representative	executive director	
	Aurora Alimentos Central Cooperative representative	innovation	
	Advisory service consultant	innovation and animal health	
	Advisory service consultant	innovation and communication	5
Science	Research governmental company	economics	
	Research governmental company	genetics	
	Research governmental company	environment and sociology	
	Research governmental company	animal health	
	Research governmental company	environment	
	University	education	
	Santa Catarina Company for Agricultural Research and Rural Extension	innovation	7
Non-governmental organizations	Lambari Consortium	executive director	
	World Animal Protection Brazil	sustainable agriculture and innovation	
	Santa Catarina Animal Health Institute	animal health, environment, and education	
	Santa Catarina Agriculture Association	president	4
Government/policymakers	Santa Catarina Agriculture, Livestock, and Fishery Department	secretary	
	Santa Catarina Agriculture, Livestock, and Fishery Department	animal health	
	Brazilian Ministry of Agriculture, Livestock, and Supply	pig production director	
	Parliamentary Group of Agriculture in the Federal Chamber	federal deputy	
	Parliamentary Group of Pig Production in the Santa Catarina Chamber	state deputy and president	
	Parliamentary Group of Pig Production in the Santa Catarina Chamber	state deputy and former president	
	Parliamentary Group of Pig Production in the Santa Catarina Chamber	state deputy	7
Total			41

Appendix 2

List of core and additional secondary data, 2017

Type of secondary data	Core secondary data	Additional secondary data	Total
Books	The economics and organization of Brazilian agriculture – Fábio Chaddad (2016)		
	Mapping of Brazilian pork chain – SEBRAE and ABCS (2016)		
	Pig production: theory and practice – ABCS (2014)		
	Swine cooking in Brazil: Quality from the field to the table – Arthur Bosísio, Raul Lody, Jean Porto Vilas-Boas (2003)		
	Sonho, desafio e tecnologia: 35 anos de contribuições da Embrapa Suínos e Aves – Jean Vilas-Boas, Dirceu Talamini, Gerson Scheuermann, Gilberto Schimidt (Harrison, Prenkert, Olsen and Hoholm, 2011)		
	Suinocultura e meio ambiente em Santa Catarina: Indicadores de desempenho e avaliação sócio-econômica – Cláudio Miranda (2009)		6
Scientific papers	Dimensões Econômicas e Organizacionais da Cadeia Produtiva da Carne Suína – Marcelo Miele (2006)		
	A sustentabilidade econômica e social da produção e frango e suínos em Santa Catarina e no Brasil – Jonas Irineu dos Santos Filho (2012)		
	A contribuição da Embrapa na Geração de Novas Tecnologias para Suinocultura e Avicultura – Dirceu Talamini et al. (2014)		3

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Type of secondary data	Core secondary data	Additional secondary data	Total
Policy briefs	Integration Law – issued on May 17, 2016.		1
Official public reports	Censo Agropecuário Brasileiro – IBGE (2006)		1
Media articles published in newspapers and magazines	Guia Gessulli da Suinocultura Industrial – Revista Suinocultura Industrial (2015)		1
Annual reports		ABPA Annual Report 2014 – ABPA (2014) ABPA Annual Report 2015 – ABPA (2015) Pig Production Magazine Nº 14 – ABCS (2015) Pig Production Magazine Nº 15 – ABCS (2015)	4
Total			16

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jrurstud.2021.11.025.

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