frontiers in Sustainable Food Systems

ORIGINAL RESEARCH
published: 11 January 2022
doi: 10.3389/fsufs.2021.741057

On (Dis)Connections and Transformations: The Role of the Agricultural Innovation System in the Adoption of Improved Forages in Colombia

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Feeding improvement strategies are key in increasing cattle productivity and reducing its environmental footprint. Nevertheless, Colombian tropical cattle systems still feature serious deficiencies in both forage quality and availability. As a result of past and on-going forage Research and Development (R&D) processes, institutions have released 23 grass and legume cultivars of superior characteristics in terms of forage quality, supply, or adaptation to different soil and climate conditions, while providing numerous environmental benefits. However, low levels of adoption are observed: although R&D processes are a necessary condition for adoption, they are still not sufficient to guarantee agricultural technification in Colombia. The ultimate success occurs only when end-users make effective use of a technology–a link constantly interrupted. Agricultural innovation requires complex processes of interaction in which knowledge is shared amongst organizations involved in the Agricultural Innovation System (AIS), namely: suitable links, attitudes, practices, governance structures, and policies. The objective of this study is to identify limitations and opportunities in R&D, adoption, and diffusion of forage technologies in Colombia from an AIS perspective. Particularly, we present a study case pertaining to research institutions only, to (a) map the involved actors and describe their roles and links, and (b) identify the events that marked the evolution of the AIS and the course of forage R&D in its research-related components. We applied a qualitative methodology based on focus group discussions, in-depth interviews, literature review, and historical analysis. Results show that the complex nature of institutions and the interactions between them determine the historical transformation of diffusion of forage technologies. The lack of connection between institutions and the weak intensity of the relationships, prevent the convergence of interests and objectives, leading to vicious cycles that hamper technology adoption. Insufficient synchronization between institutions of different nature (and even between those that share similar objectives) results in efficiency losses due to an unnecessary repetition of activities and processes. We provide recommendations for policy- and decision-makers that will help in both a restructuration of the AIS and a better allocation of funds for R&D, and thus support the development of more effective pathways for forage adoption and scaling.

Keywords: improved forages, research and development, AIS, technology adoption, sustainable intensification

OPEN ACCESS

Edited by:
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Specialty section:
This article was submitted to Climate-Smart Food Systems, a section of the journal Frontiers in Sustainable Food Systems

Received: *14 July 2021*
Accepted: *14 December 2021*
Published: *11 January 2022*

Citation:
Enciso K, Triana N, Díaz M and Burkart S (2022) On (Dis)Connections and Transformations: The Role of the Agricultural Innovation System in the Adoption of Improved Forages in Colombia. Front. Sustain. Food Syst. 5:741057. doi: 10.3389/fsufs.2021.741057

INTRODUCTION

It is no secret to anyone that the livestock industry is constantly growing and evolving. It is estimated that by 2027, the demand for livestock products will increase by 15.5% worldwide in response to population growth, urbanization and increased incomes in developing countries (OECD/FAO, 2020). It is also well-known that Latin America and the Caribbean at large hold an essential place and role in the livestock sector worldwide, as they contribute more than 25% of the production of beef and 10% of milk (CEPAL, 2017). This activity generates internal and external benefits, guaranteeing to a certain extent food security goals in countries, boosting their economies. This livestock trend in the region is not only historically traceable, but is projected into a promising future. According to the Inter-American Development Bank–BID (2018) and based on world population growth, it is projected that by 2050 meat consumption will increase by 100%, a scenario that would favor Latin American producers given its geographic location and access to human and natural resources. Hence, the supply response to this increase will be located mainly in developing countries (where forage-based systems predominate), according to the availability of resources and the possibilities of increasing productivity (OECD/FAO, 2020). Although historically larger livestock production numbers have been achieved in comparable periods (for example, it tripled between 1980 and 2002 according to Rajalahti et al., 2008), the context has now radically changed. There is a growing scarcity of natural resources (e.g., soil fertility, water and soil availability), as well as political pressure on the incorporation of better environmental practices. This constant political and social pressure seeks to promote actions aimed at reducing the environmental impacts of the livestock sector, being then the main challenge of tropical ranching to increase the efficiency of productive systems, mitigate the environmental impact, and advance in adaptative efforts in the advent of climate change. In addition to this, other impacts and improvements in the livestock industry and its actors become urgent, not only at the primary producer level (in terms of the promotion and implementation of sustainable intensification practices) (Rao et al., 2015), but also in the more equitable and environmentally sustainable value chain structuring processes, as they encourage the elaboration of differentiated products (Charry et al., 2019). Currently, a multiplicity of actors and sectors, political, economic, and academic, are promoting livestock agendas toward sustainability.

In a context of urgent reinvention and growing demand, the livestock industry finds it decisive to implement agricultural innovations, such as improved forages. The deficiencies in the quality of the forages appear as a constant in the tropical territories where cattle activity takes place (Peters et al., 2012). Improving said quality, as well as the availability of food, has been established as one of the key strategies to increase productivity and reduce the environmental footprint (Gerber et al., 2013; Herrero et al., 2013). Thus, and as a result of the Research and Development processes in Latin America (R&D) (some of which we address in this article), 26 cultivars have been released in Colombia, including grasses and legumes that have shown to have better characteristics in terms of quality, forage supply, adaptation to different soil and climate conditions, and various environmental benefits (Peters et al., 2012; Rao et al., 2015; Enciso et al., 2019).

However, and despite the fact that there is little evidence in this regard, low levels of adoption of these forage technologies have been observed (Shelton et al., 2005; White et al., 2013; Labarta et al., 2017). This shows, at least partially, that while research processes are a necessary condition, they are not sufficient to guarantee agricultural innovation. The success of R&D processes occurs when producers make effective use of technology, a link that still falters in the Colombian case. Globally, the impacts on adoption have been evaluated for less than half of the 118 million hectares (Mhas) documented to have improved forages (White et al., 2013). In the Colombian case, the national forage adoption rate is around 62% with respect to the total area in pastures in the lower tropics, being the varieties *B. humidicola* and *B. decumbens* (pastures introduced in the 70s) the most adopted (Labarta et al., 2017). Yet, many of these areas are in some state of degradation (IDEAM UDCA, 2015; Rincón et al., 2018). An adoption of <1% is estimated for the case of hybrids of the Brachiaria genus, as a result of the breeding work carried out by the International Center for Tropical Agriculture (CIAT) in Colombia (Labarta et al., 2017).

The analysis of forage technology adoption processes in Colombia indicate decisive elements in the understanding of the causal relationship between producers and their adoption behavior, but to date there are no explanatory studies that offer a macro perspective to understand the barriers in the access to technology and dissemination mechanisms (see Vera and Seré, 1989; Seré et al., 1993; Rivas and Holmann, 2004; and more recent approaches in White et al., 2013 and Labarta et al., 2017). Available literature has explained, to a certain extent, the factors that limit or promote the adoption of technologies from the perspective of the primary producer, delving into the socio-demographic characteristics of the unity, and the conditions of the enablers, such as access to credit and technical assistance (e.g., Lapar and Ehui, 2004; Jera and Ajayi, 2008; Dill et al., 2015). Some revised studies mainly describe adoption processes in regions of East Africa and Latin America, focusing on the identification of adoption factors mostly from a primary producer's perspective with both quantitative and qualitative approaches. Although still privileging primary producer's perspectives, qualitative studies have done more to document and unveil the experiences and lessons learned related to the adoption of improved forages, taking analysis one step further (e.g., Reiber et al., 2013; Gil et al., 2015; Ashley et al., 2018). Although theoretically and methodologically vital, here we point out that these studies lack deeper perspectives that allow historical decision-making, and thus highlight the complex relationships between agents and institutions that participate in the adoption and diffusion of agricultural technologies. Although it is undeniable that the scientific and research sector plays a fundamental role in the creation of technologies that help to increase productivity, mitigate the effects of climate change, and improve the quality of life of small producers (especially when working in partnering with the public sector and non-governmental organizations),

these investments turn out to be insufficient to enable agricultural innovation. This process requires the existence of broader competencies, links, enabling attitudes, practices, governance structures, and policies that facilitate the productive use of the knowledge generated (The World Bank, 2006). This comprises the set of all organizations and people (public and private) involved in the generation, dissemination, adoption, and social and economic use of new agricultural technologies (The World Bank, 2006; Hambly et al., 2012). The network formed in this process, and the conceptual lens of this study, is called the Agricultural Innovation System (AIS).

The AIS approach recognizes that innovation is a dynamic and complex process of interaction between different activities, actors and relationships associated with the creation and transmission of innovation to its productive use (The World Bank, 2006). This approach recognizes the role of actors, markets, institutions, political contexts, and networks in the adoption of new technologies and, therefore, in the evolution of innovation in a system (Rajalahti et al., 2008). Different authors have used the AIS approach as a framework to identify conditions that limit or promote the adoption of technologies in the rural sector (e.g., Spielman et al., 2011; Kebebe, 2018). Among the factors commonly mentioned are: (1) the scarce presence of public policies on innovation and agriculture; (2) problems related to asymmetries in communication; (3) weak links and lack of trust between actors; and (4) norms and cultural attributes of society that impede development and innovation processes, as well as behaviors, practices and attitudes that condition the roles and interactions between actors.

Taking into account the comprehensive nature of the AIS approach, the objective of this study is, through the use of it, to identify limitations and opportunities in the process of development, adoption, and diffusion of forage technologies in Colombia for the case of the actors related to the research/science component. For this we have decided to integrate qualitative approaches when addressing the phenomenon, with the intention of providing a detailed analysis that addresses the nature of inter-actor relationships and the contingencies that determine their transformations. To do so, we rethink the processes of adoption and diffusion of forage technologies through a historical perspective, highlighting the variables and actors that participate in said processes. In addition to highlighting the importance and delving into the investigative component, this article identifies some of the main events that have directed the course of research and dissemination of forage technologies in the country; and maps the actors that are part of the innovation system, describing their roles, links and attitudes, and the way in which they have catapulted or hindered forage innovation processes.

As mentioned before, the network formed in this process is called the Agricultural Innovation System (AIS), a network of actors and institutions that we are just beginning to elucidate. Thus, identifying the limitations and opportunities in the process of development, adoption and diffusion of forage technologies in Colombia implies an understanding of the dynamics that shaped inter-institutional relations, as well as their internal functioning mechanisms. This document is then structured as follows: first, it specifies the methodological tools used for the analysis. Subsequently, it delves into the historical context that has directed the course of research and dissemination of forage technologies in the country, laying the foundations for the analysis. Thirdly, links and levels of influence between the different actors and institutions of the research component are analyzed and mapped. The last two sections expose the bottlenecks and main obstacles that stand in the way of the proper development of the innovation and diffusion processes in general, and provide some ideas on future steps to follow in the matter.

MATERIALS AND METHODS

In order to identify the factors that limit or promote the development, diffusion, and adoption of forage technologies in Colombia, this study used qualitative methodologies, including: literature review, focus groups, and in-depth interviews. The Net-map tool was used to identify actors, their roles and importance in the AIS. The qualitative data generated was analyzed using the following tools: (i) transcription of interviews and focus group meeting; (ii) coding and categorization of key aspects; and (iii) interpretation of the information. The analytical purpose of the instruments used is explained in detail below.

Net Map Tool

Net-map is a participatory mapping research method developed by Schiffer (2007), and has been applied in different agricultural research problems to analyze networks and power dynamics in the promotion of technologies (e.g., Aberman et al., 2015; Ilukor et al., 2015; Daum and Birner, 2017; Lubungue and Birner, 2018). In the present study, the application of the tool was carried out through a focus group session, made up of five participants (active researchers from CIAT's Tropical Forages program), in-depth interviews, and a review of secondary sources. The application of this tool was directed to the research component of the AIS of forage technologies. Thus, the following objectives were proposed for the focus group discussion: (i) identify the actors that are part of the AIS in forage technologies at the national level, and (ii) describe the roles, links, and attitudes of the agents involved in the activities of the AIS.

The Net-map process was divided into two main activities. First, the participants identified the main people, institutions, and organizations that participate in the process of development, dissemination, and adoption of forage technologies in Colombia. Each participant wrote the name of the identified actors on separate cards (one actor per card), also writing down information about the role they play within the process and their level of influence in the AIS. The latter was defined as the actor's ability to influence the specific problem. The measurement of the level of influence was established using a Likert-type scale from 0 (no influence) to 4 (greater degree of influence). At this point, it should be mentioned that the participants in the group session are part of the population under study, and each one has experienced the process from different perspectives. For this reason, different colored cards were assigned to each participant, in order to identify the

responses of each one. Next, the cards were collected and grouped according to the different components and distributed on a sheet of paper. During this activity, various questions for discussion and reflection were generated among the participants, related to the absence of actors in some component, and the divergences between roles and influences presented by the participants.

Second, the links, influences, and attitudes of the actors identified in the previous activity were identified. In this section, an open discussion was held among the participants, based on the following questions posed by the facilitator: which of the identified actors have any link to each other? What is the direction of the link (one-way or two-way)? What is the type of exchange (information flow, use of resources, planning, training, etc.)? And what is the strength of this relationship (weak, medium, strong)? According to the response of the participants, arrows were drawn, indicating the existence of a relationship and its characteristics. In the development of this activity, various discussion questions were generated associated with the characteristics of the relationships perceived between the actors, about the attitudes and practices that have restricted and/or promoted the interaction, and about the possible limitations that may have hindered or restricted the linking activities between the different actors. The full program of the focus group session and an implementation guide for the facilitator are presented in the **Supplementary Material**.

In-depth Interviews

Based on the focus group session and the review of secondary sources, some of the different actors that are part of the AIS were identified, which belong to various components. This information was organized in a spreadsheet, grouping the actors according to their membership in each component. Based on this information, the people to interview were selected, according to their experience and relevance within the processes of development, dissemination, and adoption of improved forages. The in-depth interviews (12 in total) were conducted between September 2019 and March 2020. Of these interviews, six focused on relevant actors in agricultural research (CIAT, Agrosavia, CIPAV), five on private sector agents (PAPALOTLA, ALQUERIA, MATSUDA, SEMILLANO, SAENZ FETY) (to understand their relationship with the research component and its actors) and a relevant actor in the field of politics in agriculture in Colombia that offered a general panorama on the matter (ICA). The interviews followed a logical format of open questions, each one lasting ∼1.5 h. For each interview, between 5 and 7 questions were selected from a comprehensive guide that included relevant topics for this research, previously carried out by the authors. This guide contains a general list of questions that are grouped into the following categories: (i) roles, attitudes, and practices, (ii) historical moments, (iii) patterns of interaction between actors, (iv) facilitating environment, and (v) gender inclusion. The selection of the questions was made according to the profile of each actor to be interviewed, prior to the interview. Six of the 12 interviews were conducted remotely, and the remainder in person.

Literature Review

Regarding secondary sources, long-standing studies were integrated on the establishment of livestock in Colombia and the continuous state and private searches to promote through the use of selected pastures) a productive and extensive and continuous livestock sector throughout the Twentieth century (1900–2000). This selection was focused in the existing literature regarding livestock, livestock practices in Colombia and Latin America at large, and improved forages. Our query included reports published by research institutions, peer-reviewed articles and databases. The search included documents published from 1980 to 2020. Conducting in-depth interviews allowed the integration of issues related to the change of research institutions and agendas, while delving into the gradual transformation of social relations that determine the course of research programs and projects. Choosing as informants subjects with a long history in their respective institutions enabled us to obtain a more precise overview of the changes over time of the institutions and professionals linked to the research field in livestock.

CONTEXTUAL AND HISTORICAL FRAMEWORK

Scientific literature conceptualizes improved forages as species that present superior agronomic characteristics compared to native forages and that, in addition, adapt to the agroecological conditions of a given region (Shelton et al., 2005; White et al., 2013; Labarta et al., 2017). These forages are the result of improvement processes, which may include: (i) selection of materials from germplasm banks according to a previous evaluation of visual characteristics, adaptability, forage production, seed, nutritional quality, and animal response (e.g., *Brachiaria*, *Megathyrsus*, *Cenchrus*, *Leucaena*, *Cratylia*, *Arachis*, among others); and (ii) genetic improvement of a material in which desirable characteristics of the parents are combined (e.g., *Brachiaria* hybrid CIAT 36061 cv. Mulato I, *Brachiaria* hybrid CIAT 36087 cv. Mulato II, and *Brachiaria* hybrid CIAT BR 02/1752 cv. Cayman). In general terms, the process of multiplication and diffusion of the seeds/vegetative materials of varieties already formally released, usually follows two routes: formal and informal.

In the formal route, cultivars are developed by a national research institution (e.g., Agrosavia) or private company (e.g., Papalotla) based on a release proposal (breeding by selection or plant breeding). Some materials in this group are: *Brachiaria brizantha* cv. Toledo, *Brachiaria humidicola* cv. Humidicola, *Arachis pintoi* cv. Forage Mani. Under this route, 26 cultivars have been released in Colombia, mainly for low-tropical conditions. In **Table 1,** we present a list of the total improved forages released in Colombia. On the other side, in the informal route, the cultivar is introduced to the country by an individual and/or national seed company which initiates the distribution and/or dissemination. As an example, there are materials in commercial use such as: *Decumbens* grass (*Brachiaria decumbens* CIAT 606), Tanzania 1 grass (*Megathyrsus maximus* CIAT 16031), Maralfalfa grass, Guinea Massai grass (*Megathyrsus*

TABLE 1 | Forage species released in Colombia.

Region		Genus and species	Accession	Variety name	Year of release	Releasing institution	Adoption registration year	Adoption rate (%)	Commercialization
Gramineae	Lower tropics (0–2,000 m elevation)	*Brachiaria brizantha*	CIAT 26646	La libertad	1987	ICA	2016	2.8	No
			CIAT 26110	Toledo	2002	Corpoica	2016	1.24	Yes
			CIAT 26124	Caporal	2021	Corpoica	N.D	ND	No
		Brachiaria humidicola	CIAT 679	Pasto humidicola	1992	Corpoica	2016	22.6	Yes
			CIAT 6133	Llanero	1987	ICA	2016	8.15	Yes
		Brachiaria hibrido	CIAT 36061	Mulato	2003	Papalotla	2016	0.05	Yes
			CIAT 36087	Mulato II	2005	Papalotla	2016	0.03	Yes
			BR02/1752	Cayman	2013	Papalotla	N.D	N.D	Yes
		Sorgo forrajero JJT-18		Sorgo dulce Corpoic JJT-18	2014	Corpoica	N.D	N.D	No
		Andropogon gayanus	CIAT 621	Carimagua 1	1980	ICA	N.D	N.D	No
		Megathyrsus maximus	CIAT 6799	Agrosavia sabanera	2018	Agrosavia	N.D	N.D	No
Fabaceae	Lower tropics (0–2,000 m elevation)	*Arachis pintoi*	17434	Mani forrajero	1992	Corpoica	2016	0.1	Yes
			22160	Centauro	2020	Agrosavia	N.D	N.D	No
		Centrosema acutifolium	5277	Vichada	1987	ICA	N.D	N.D	No
		Cratylia argentea	CIAT 18516+18668	Veranera	2002	Corpoica	N.D	N.D	No
		Desmodium heterocarpon	13651	Maquenque	2002	Corpoica	N.D	N.D	No
		Leucaena leucocephala	21888	Romelia	1992	Cenicafe	N.D	N.D	No
		Stylosanthes capitata	10280	Capica	1983	Corpoica	N.D	N.D	Yes
		Vigna unguiculata		Sinu		Corpoica			
Avena	Higher tropics	ICA Bacatá			1963	ICA	N.D	N.D	No
		ICA Soracá			1965	ICA	N.D	N.D	No
		ICA Gualcalá			1968	ICA	N.D	N.D	No
		ICA Cajicá			1976	ICA	N.D	N.D	Yes
		Avena Obonuco Avenar			2003	Corpoica	N.D	N.D	Yes
		Avena Forrajera Altoandina			2018	Agrosavia	N.D	N.D	No

Own elaboration based on Peters et al. (2011), Labarta et al. (2017), and expert consultation and information provided by seed distributors. ND: no data available. Note: In 1992, ICA was restructured and the research activities passed to the newly created Corpoica; Corpoica is now called AGROSAVIA.

maximus cv. Massai), *Stylosanthes* cv. Campo Grande (Mix between *Stylosanthes capitata* and *Stylosanthes macrocephala*), Pennisetum cv. Cuba 22, and *Pennisetum* cv. Clone 51.

At the national level, we find that there is an adoption level of 34.97% of fodder released under formality channels. Of this percentage, 34.89% corresponded to introduced species of the genus *B. humidicola* and *B. brizantha*; introduced ∼30 years ago (Labarta et al., 2017). In relation to hybrid forages (Mulato I and Mulato II) an adoption level of 0.08% was registered (Labarta et al., 2017), while the varieties released informally such as *B. decumbens, M. maximus* cv. Tanzania, and cv. Mombaza report an adoption percentage of 0.98, 0.29, and 1.61%, respectively (Labarta et al., 2017).

Different studies have carried out, during the last nine decades, documentations of the benefits and costs associated with the adoption of improved forages (see **Table 2**). These studies show the potential of improved forages to improve animal production and contribute to the sustainability of production systems at different scales. In particular, CIAT developed the LivestockPlus concept, demonstrating how the introduction of improved forages in the tropics can lead to sustainable intensification, producing multiple social, economic, and environmental benefits (Rao et al., 2015). These benefits are mainly associated with the increase in the availability and quality of pastures, which results in better indicators of animal development, productivity, and profitability of the livestock activity. In addition, improvements in the quality of feed allows improving the ruminal fermentation process and, therefore, reducing greenhouse gas (GHG) emissions, and achieving greater intensification of the livestock activity (Oliveira et al., 2007; Hristov et al., 2013). It is necessary to clarify that these potential benefits of the use of improved forages depend on the appropriate agroecological and management conditions.

The introduction of technologies to improve the livestock sector has taken place for more than a century (Van Ausdal, 2012). Between 1850 and 1950, the nascent cattle ranchers of Colombia made significant efforts to improve their agricultural practices through the introduction of new breeds and bovine crosses, the improvement of fences and farm care, as well as the introduction of Africanized pastures [e.g., Pará (*Brachiaria mutica*), guinea (*Panicum maximum*)], among others (Rao et al., 1998; Rincón et al., 2010). Since the introduction of pastures of the Brachiaria genus, there has been a rapid and sustained growth of grazing areas in the country: by 1900 there were already two million hectares sown in Pará and Guinea, and by 1958 this number amounted to 10 million, this is, one third of the grazing land of the entire national territory (Van Ausdal, 2012). Said dissemination and adoption processes were spontaneous and massive, they did not follow established guidelines or regulations. They obeyed, rather, to the commercial need to establish a solid industry (especially meat) with an export industry that was never consolidated (Rao et al., 1998; Rincón et al., 2010; Van Ausdal, 2012; Ponce de León-Calero, 2019).

Two historical moments stand out as decisive in regards to R&D processes: the so-called "green revolution" and the advent of neoliberal economic policies in developing Latin American countries (Lynam and Byerlee, 2017). The first moment took place between the 1960s and 1970s, and was marked by an increase in agricultural investment and marked concerns about productivity and quality of life in rural settings, triggered by the need to promote agricultural development in a world increasingly unequal caught up in the political ups and downs of the Cold War (Lynam and Byerlee, 2017; Ponce de León-Calero, 2019). The flourishing and consolidation of programs such as CIAT's Tropical Forages and Agrosavia (Colombian Agricultural Research Corporation former CORPOICA, in Colombia) are also highlighted here, which shows a growing multilateral interest in promoting agricultural innovation processes (Lynam and Byerlee, 2017).

The second moment is framed by the political and economic agendas of Latin American governments (including Colombia) at the beginning of the 1990s, within the framework of neoliberal transformations and economic flexibility (Tirado-Mejia, 1997; Palacios and Stoller, 2006; Van Ausdal, 2012; Ponce de León-Calero, 2019). Previously solid institutions dedicated to research (such as Agrosavia) underwent important restructuring processes due to budget cuts limiting their research possibilities, the continuation and monitoring of ongoing projects and adequate and complete process of technological diffusion. The changes and contingencies experienced by institutions such as Agrosavia show that, as far as agricultural research processes and actors are concerned, continued state funding is necessary. From the interviews carried out with the actors in agricultural research circuits, we were able to establish the causality between state funding and the success or continuity of research programs, as several of the interviewed informants narrated the processes of transformation and historical decline of their scientific agendas because of budget cuts. Untimely budget reductions, as well as the relegation of investigative processes to second place, have undoubtedly been determining factors for efficient dissemination processes, thus affecting the viability of adoption processes. It should be noted that since the 1980s the national research institution Agrosavia has released new forage species, grasses, and legumes, previously evaluated by CIAT. Among these, the cultivars of *Brachiaria dictyoneura* (cv. Pasto Llanero, 1987), *B. brizantha* (cv. La Libertad, 1987), and *B. humidicola* (cv. Humidicola, 1990) stand out. Likewise, the creation in 1979 of the International Tropical Pasture Evaluation Network Foundation (RIEPT) stands out as a fundamental milestone to promote research in the subject and discuss the use of methodologies for evaluating forage technologies (Lynam and Byerlee, 2017). The existence of the RIEPT originated an invaluable database of forages studied and analyzed in detail and allowed the distribution of germplasm among researchers dedicated to the matter, materializing the advances of their research and strengthening institutional relationships between various groups and scientific niches (Lynam and Byerlee, 2017).Below are explained in more detail (i) key processes and their influence on the R&D processes of forage technologies in Colombia and (ii) the agents of the process and their respective interactions.

TABLE 2 | Benefits and costs of improved forages.

Benefits and costs		Effects at different scales			References
Direct benefit	**Impact**	**Farm**	**Regional**	**Global**	
Increment in the availability and nutritional quality of forage	Increment in milk and beef production				Rincón et al., 2010; Rao et al., 2014, 2015; Maass et al., 2015
	Higher number of animal heads per unit area	✓	✓		
	Better productive parameters of animal development (e.g., mortality and birth rate)				
	Social impact: improvement in income, food security and nutrition.				
Reduction of enteric methane emissions (CH_4)	Reduction of GHG emissions per unit of livestock product, given the improvement in feed efficiency. Mitigation and adaptation to climate change				Oliveira et al., 2007; Hristov et al., 2013; Peters et al., 2013; Herrero et al., 2016
Increase in atmospheric nitrogen (N) fixation (legumes)					Shelton and Dalzell, 2007; Reckling et al., 2016
Carbon (CO_2) accumulation in the soil					Oliveira et al., 2007; Soussana et al., 2010; Peters et al., 2013; Rao et al., 2015
Reduction of nitrous oxide (NO_2) emissions, associated with Biological Nitrification Inhibition (BNI)			✓	✓	Subbarao et al., 2009, 2017; Moreta et al., 2014; Karwat et al., 2017; Nuñez et al., 2018
Improvement of soil quality indicators	Improvement of the biological conditions of the soil (increase of biological indices of diversity of micro and macro fauna)				Rousseau et al., 2013; Lavelle et al., 2014; Rao et al., 2015
	Improvement of the physical conditions of the soil (reduction of erosion, compaction, and apparent density)				
Costs					
Establishment of materials (increased use of inputs, labor, equipment)		✓			Carey and Zilberman, 2002; Pannell et al., 2006
New knowledge and skills to maintain the technologies					Thomas and Sumberg, 1995; Lapar and Ehui, 2004
Development of appropriate extension and training packages			✓		Reiber et al., 2013
High perceived risk/uncertainty of technology		✓			Marra et al., 2003

Own elaboration based on the references mentioned.

RESULTS

Mapping of Actors

The information collected shows that the AIS in Colombia for improved forages includes actors from both public and private sectors. **Table 3** presents the list of actors and functions of the AIS for improved forages in Colombia, according to secondary sources, the focus group, and interviews. These actors can be grouped into the following six main components: (i) Politics; (ii) R&D; (iii) Extension, training and information; (iv) Supply of seeds; (v) Financing, and (vi) Primary producer. Each organization can fulfill one or different functions within the system: generation of knowledge, coordination, supervision and control of dissemination processes, bridging, or intermediary institutions, generation of spaces for the articulation of actors, or support structures at the institutional and political level (**Figure 1**).

The component of R&D consists of a total of 11 institutions dedicated to research on tropical forages. It includes national, regional, international and private research institutions. Among national research, Agrosavia, is the main public organization dedicated to research in the sector. It has 13 regional research centers (CIR) spread throughout the country, as well as offices in 10 locations. Of the total number of Agrosavia centers, eight include livestock and forages within their research lines. Mainly, Agrosavia has had a great impact on the development and release of new forage materials through the evaluation and selection of germplasm. At the international level, the Tropical Forages program of the International Center for Tropical Agriculture (CIAT) stands out for its role in the development of plant breeding hybrids, evaluation of materials, and the promotion of concepts of sustainable intensification through improved pastures. Likewise, CIAT has one of the largest collections of forage accessions in its germplasm bank, estimated at 22,694 accessions (from 75 countries). Historically, both CIAT and Agrosavia were identified as vital agents and leaders within the improved forage development processes. At the regional level, public universities have played a fundamental role both in the evaluation of technologies and in their application and promotion, through specific scaling-up projects. Among these,

TABLE 3 | List of actors and functions of the AIS for improved forages in Colombia.

Component/Category actor			Functions														
			F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16
Policy	Ministry of Agriculture and Rural Development (MADR)		**x**	**x**	**x**	**x**	**x**						**x**				**x**	
	Ministry of Environment and Sustainable Development (MADS)			**x**	**x**													
	Colombian Roundtable for Sustainable Cattle (MGS-Col)		**x**		**x**	**x**												
	Colombian Agricultural Institute (ICA)			**x**	**x**		**x**											
	Rural Agricultural Planning Unit (UPRA)				**x**		**x**											
	Departmental Agriculture Secretariats				**x**	**x**	**x**						**x**					
Research and development	National research	The Colombian Agricultural Research Corporation (Agrosavia)				x		x	x	x	x							
		Center for Research in Sustainable Systems of Agricultural Production (CIPAV)				x		x	x	x	x							
	International research	International Center for Tropical Agriculture (CIAT), Tropical forages program				x		x	x		x							
		The Tropical Agricultural Research and Higher Education Center (CATIE)				x			x		x			x				
	Regional research	University of Cauca- Research group NUTRIFACA				x			x		x							
		National University of Colombia				x			x		x							
		University of Antioquia- Agricultural Sciences				x			x									

(Continued)

TABLE 3 | Continued

Component/Category actor			Functions															
			F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16
		University of Llanos- Research group in Agroforestry				x			x									
		University of Nariño-FISE PROBIOTEC				x			x									
		University of Córdoba-Research group in tropical animal production				x			x									
	Private research	Papalotla							x	x	x							
Extension, training, and information	Colombian Cattle Federation (FEDEGÁN)				x	x					x				x			
	Agricultural extension	Municipal Units for Technical Assistance in Agriculture (UMATAs)											**x**					
	Training and education	National Training Service (SENA)											**x**	**x**				
		Private sector (e.g., Nestlé, Alquería, Alpina) and Outreach initiatives (e.g., Sustainable Colombian Cattle Project)												**x**				
	NGO's	Food and Agriculture Organization of the United Nations –(FAO)									**x**		**x**					
		GANSO									**x**		**x**					
Seed supply	Papalotla Colombia SAS								x	x	x	x			x		x	

(Continued)

TABLE 3 | Continued

Component/Category actor			Functions													
			F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16
	Sáenz Faety, Impulsores Internacionales, Semillas & Semillas, Agrosemillas, among others											x			x			
	Seed producers in Brazil (e.g., EMBRAPA)							x	x			x						
Financing	Financial services	The Colombian Fund for the Financing of the Agricultural Sector (FINAGRO)														**x**		
		Banco Agrario of Colombia														**x**		
		Private banks														**x**		
		Producer associations and cooperatives														**x**		
		Informal credit														**x**		
	R&D financing	Ministry of Agriculture and Rural Development (MADR), Grupo Papalotla, high-income countries and international agencies, donors															**x**	
Primary producer	Producer associations and cooperatives										**x**		**x**	**x**				**x**
	Individual cattle producers										**x**							**x**

F1 Promotion of spaces for articulation, coordination and integration of actors.
F2 Design of regulatory and normative frameworks.
F3 Execution and supervision of public policies.
F4 Design and execution of programs and/or projects.
F5 Coordination, supervision and control within the dissemination processes.
F6 Technology development.
F7 Technology assessment (at the experimental level).
F8 Technology release.
F9 Promotion and demonstration of technology.
F10 Technical advice and information.
F11 Extension and/or agricultural technical assistance.
F12 Training and certification of labor competencies.
F13 Seed multiplication and/or distribution.
F14 Financial services.
F15 Research and development financing.
F16 Demand and use of technology.

Source: Own elaboration.

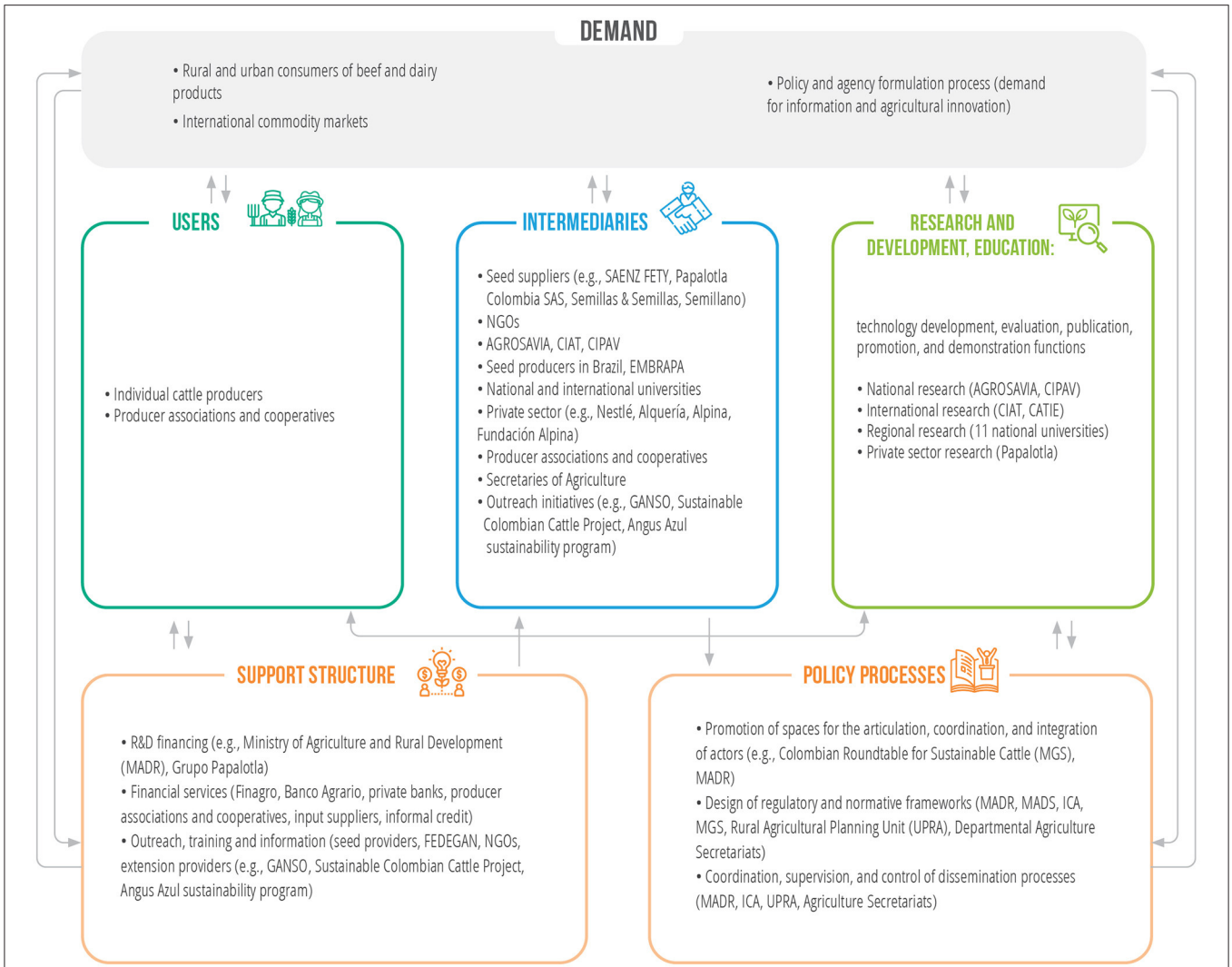

FIGURE 1 | Main agents of AIS for improved forages in Colombia.

the following stand out: The National University of Colombia and the University of Nariño (research conditions of the high tropics).

Bridging organizations or intermediaries, in particular, extension and training services, seed supply, and producers' organizations, facilitate interaction and/or link knowledge generation of R&D agents with users of technologies. Extension services for agricultural production in Colombia go back to the 1950s. At that time, the international trend for the creation of agricultural research institutes and extension services began to grow. From that moment, rural extension services have been through important transformations and organizational arrangements toward a decentralized technical assistance at the territorial level. Currently, the national technical assistance has a framework in the law 1876 of 2017 and the guidelines for the formulation of departmental plans of agricultural extension (PDEA, as per its acronym in Spanish). PDEA are regulated by the Ministry of Agriculture and Rural Development (MADR, as per its acronym in Spanish) in the resolution 407 of 2018. According to these guidelines, there are key stakeholders for delivering extension services such as local units of technical assistance for agricultural production (also known as UMATAs, as per their acronym in Spanish), provincial centers of agrobusiness management (CPGA, as per their acronym in Spanish), the national service for vocational education (SENA, as per its acronym in Spanish), professional associations of the sector, unions, associations, and community-based organizations.

Regarding the national seed supply of improved pastures, it is carried out by commercializing companies that import seeds from Brazil, Mexico, the United States, and Canada (comparative advantages from geographical conditions). **Figure 2** shows the network of importing and exporting companies of improved forage in Colombia. These companies can be divided in two

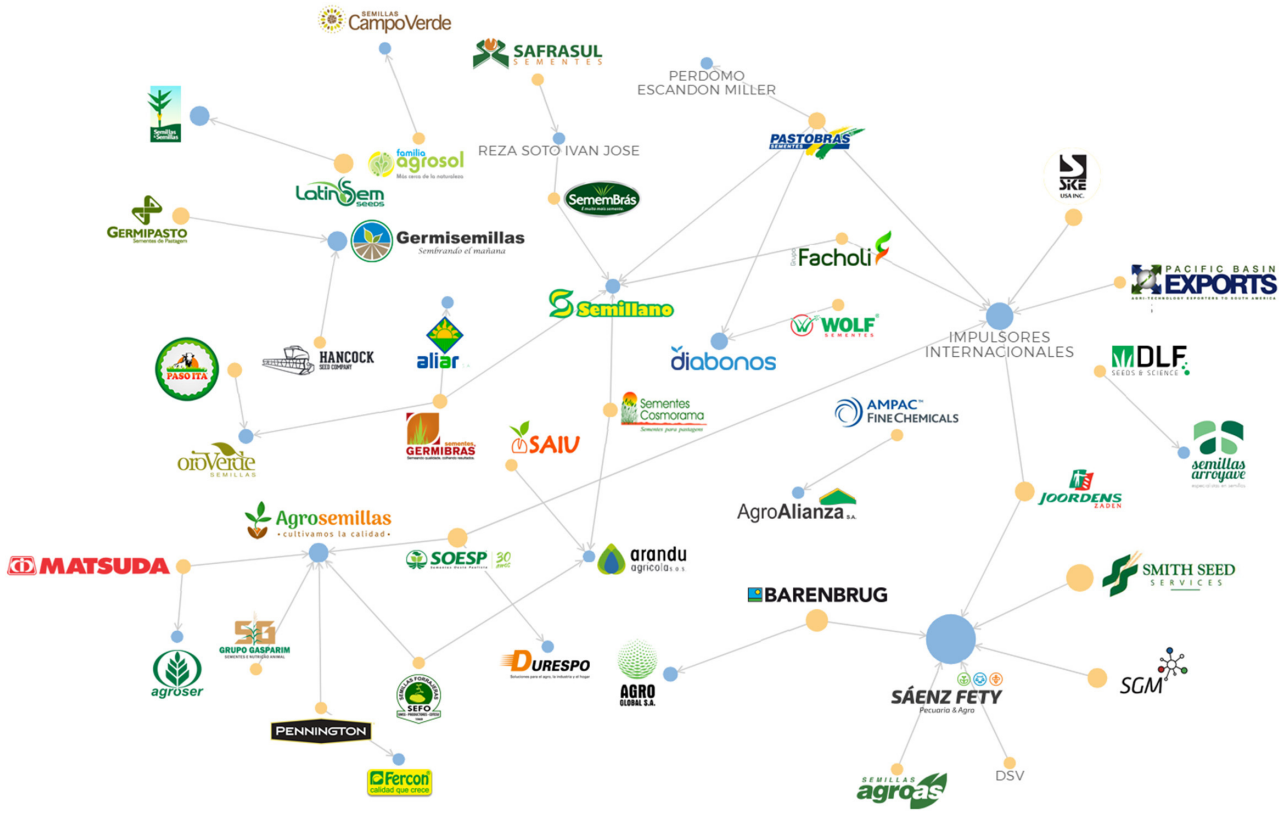

FIGURE 2 | Network of companies that import and export improved forage seeds in Colombia. Own elaboration based on trade statistics from Legiscomex (2020). Note. The blue nodes refer to the importing companies, and the yellow nodes refer to the exporting companies. The size of each node represents the level of participation regarding to the total in imports and exports, respectively.

groups: importers of introduced varieties and importers of hybrid varieties. The market of introduced varieties has a share of the 98% of all seeds commercialized nationally. This group is comprised of 27 companies. The most relevant are SAENZ FETY, Impulsores Internacionales, and Semillas & Semillas with a market share of 20, 15, and 10, 1%, respectively. These companies commercialize and distribute varieties from Brazil. For low tropics conditions (mainly the species *Brachiaria* and *Panicum*) and for high tropics conditions (mainly varieties such as Ryegrass, Alfalfa, Festucas, Pasto Azul, and clover) sourcing from the United States and Canada. The second group refers to the market of hybrids, still under development with a share of <2% of all commercialized seeds nationally. In this group, from 2017, the company Papalotla Colombia SAS imports and directly distributes through sales advisors and authorized distributors. Direct presence of Papalotla has increased the market of hybrids since 2017. They import hybrid grasses from Semillas Papalotla in Mexico and Brazil. The nationally commercialized seeds are *Brachiaria* hybrids cv. Cayman and Mulato II, with a share of 75% (32 tons in 2018) and 25% (10 tons in 2018), respectively (Rosales and Papalotla, 2019, personal communication).

All stakeholders are influenced by a context of agricultural policy, institutions, and informal general practices that might support or limit innovation processes. Stakeholders here recognize the role of the MADR for its relevance in the formulation, coordination, evaluation of agricultural and rural development policies, sustainable livestock production policy, and financing of programs and/or projects related to the development of forage technologies. Furthermore, stakeholders highlight the role of MADR in the establishment and regulation of the national policy of technical assistance for agricultural production.

Actors and Levels of Influence

Here, a linkage mapping exercise is presented, in which CIAT's relationships with other actors (that CIAT recognizes as key agents in the development and dissemination processes of improved pastures) in Colombia are analyzed. The following results are based on the focus group discussion.

Relationships between R&D institutions mainly occur for collaborative research as part of specific projects. The links are strong between some institutions (e.g., Agrosavia and CIAT and their Forages Network). In most cases, however, we observe weak links that generate duplication of research efforts and competition for resources. There are not many strong links between R&D institutions and intermediary agents such as seed

supply companies. CIAT, as exemption, has a strong link with Papalotla regarding the financing, co-development, and exchange of information on forage hybrids. The lack of other possible examples denotes a relational crisis between institutions that still needs to be overcome. Seed companies play a key role in providing technical assistance and training to primary producers, although mainly at the regional level. National universities have a high level of influence regarding the application of technologies (e.g., University of Cauca, University of Antioquia, Amazonia University, and National University of Colombia). However, this is done through specific scaling projects and requiring allies. In the interviews, it was pointed out that the impacts of dissemination processes depend on the collaboration among institutions, and that the competitive nature of funds increases the participation of universities in R&D processes.

Milk and meat trading companies have high potential in terms of technology diffusion due to their direct relationship with producers. Although these companies are key players in accompanying producers, they require a better communication with technical knowledge research and development institutions that effectively bring technological innovations closer to their target populations, harmonizing concepts, and reducing the circulation of confusing information. Currently, there are initiatives and approaches between private companies and research institutions (e.g., Fundación Alpina and CIAT). Associations and/or cooperatives of producers are recognized as having a strong role in the processes of diffusion and scaling of forage technologies. Among the roles they can fulfill are the collaboration with the research component and/or in the selection of pilot farms for the evaluation of technologies, the dissemination of information on technologies, supply of inputs, as well as training and extension among associated producers.

The MADR is identified as an actor with high influence within the processes of development and diffusion of forage technologies. This influence is associated with its role in the construction of a sustainable livestock policy at the national level, the financing of research programs in forage technologies, and the contribution to the Colombian Roundtable for Sustainable Cattle (MGS-Col). In recent years, the MADR and the Ministry of Environment and Sustainable Development (MADS) have increasingly aligned their agendas supporting sustainability more strongly. Thus, the lack of association between most of the innovation actors and the support structures has resulted in the existence of a generally weak innovation system. However, it is important to highlight outreach initiatives to strengthen institutional links and communication between actors that have been taking place in recent years, such as the participation of the main actors of the livestock sector in multi-actor platforms such as the MGS-Col, and approaches of the sector private sector and research institutions. The Rural Agricultural Planning Unit (UPRA) has a growing level of influence on livestock policy given the zoning exercise they conducted for livestock production in the country.

Bottlenecks

The mapping exercise carried out here allows us not only to identify the complexity of the AIS research component in the field of forages, but also provides insights to deepen and contextualize the existence of serious and persistent bottlenecks that affect agricultural innovation in forage matters. Below we describe the limitations that have had a direct impact on the technology adoption and diffusion processes, identified by the actors interviewed during the study.

Extensive Tradition of Livestock

Structural conditions are evident factors in discouraging sustainable intensification and, along with it, the adoption of improved species. For example, for traditional extensive ranching it is much more efficient (cost-effective) to acquire more land for the establishment of the crop than to intensify the use of a certain amount of land through the adoption of technologies. Deforestation as a result of livestock activity, an increasingly critical and urgent topic, also stands as one of the bottlenecks as far as livestock is identified as one of the main culprits behind the invasion of conservation/protected areas for the agricultural exploitation. The low cost of land in pastoral areas, and the still precarious controls over land tenure due to long-standing historical dynamics in which a fragile state predominates, favors land accumulation. This not only encourages sustained land accumulation by illegal actors (who have monopolized or decades large tracts of land, some of which are indeed dedicated to extensive livestock projects) but also encourages small livestock producers to upsurge agricultural areas instead of intensifying their production. In this way, a trend toward the purchase of land or expansion of the agricultural frontier is promoted.

Low Budget for Research

Budget cuts in the 1990s limited Colombian scientists and researchers, both in the formulation and in the follow-up and monitoring of ongoing projects. The paradigm shift in funding brought new consequences: scientists, who were dedicated solely to research work, now have as their main mission a systematic procurement of resources. This led to important distortions in the development of research agendas, fragmented personal and institutional relationships, and weakened sustained advances in the matter (e.g., programs such as the International Network for the Evaluation of Tropical Pastures -RIEPT) were eliminated. Even today there are certain misunderstandings derived from the new role of the scientist/extension worker.

Influence of Public Order Problems on Technology Diffusion Processes

On the one hand, technology transfer processes were affected as a consequence of the various dynamics of the armed conflict between the Colombian state, guerrillas, and paramilitary groups. Concrete examples of this correlation are found in the narratives about kidnappings and threats to research personnel, as well as in the uncertainty in the arrival of seeds to conflict zones. The manifest weakness of the state in disputed territories, as well as the fluctuating (and violent) political order in certain areas of the country has, without a doubt, affected the adequate implementation of extension projects, leading seed supply companies to register large economic losses. On the other hand, the consequence of the illegal drug trafficking market and

the scarce state regulation of the seed market led, between the 80s and 90s, to the importation of large quantities of them for money laundering. The existence of a poorly regulated industry facilitated its use as a "facade" between drug traffickers and cartels, which resulted in the importation of large quantities of seed with low quality standards, affecting the domestic market.

Different Objectives Causing a Low Articulation Between National R&D Institutions and Seed Companies

With the help of donors, research entities aim to evaluate and release forage seeds. However, seed production is determined primarily by their own perspective on actual demand and profitability. This disparity causes the processes of diffusion and releasement of seeds to be distorted, and that results in turn in a low impact on the adoption processes: materials are released without commercially available seed, or else, these materials are not suitable for the territories in which they are that are traded informally.

Absence/Weakness in the Social Support of the Research

According to informants, the average duration of projects for the promotion and adoption of forage technologies is 3 years. This period constitutes a limitation because it makes it difficult to adequately measure the impact and scope of the introduction of a new species, and furtherly impossible to obtain accurate data about the adoption of technologies. Scarce times hinder the evaluation of the sustained use of new species, so a complete picture on the adoption of improved pastures at the national level remains a long way off. The foregoing is also a consequence of the disarticulation between different areas and research professionals, as well as between centers and entities in charge of formulating and executing technological innovation projects.

Speculation in the Brazilian Market as a Determinant of the Livestock Landscape in Colombia

The geographical and climatic conditions of the country limit the production of forage seeds, making Colombia dependent on seeds from its Brazilian partner, the main producer in the world. This high level of dependency makes Colombia susceptible to suffering from internal shocks to the economy in Brazil; that is, in the face of a change in the perception or in the projections about the profitability of a certain crop (e.g., sorghum, corn, soybeans) or between forage varieties, companies may prefer to produce seeds of the crop or a certain variety of pasture perceived as more profitable in the short term. These changes not only occur between substitute varieties but also between crops that are not directly related to livestock, which greatly limits the options of the demanding countries. Thus, changes in the Brazilian supply derived from speculative processes lead to an impact on the price level and availability of seeds in Colombia, so that a producer can in turn vary the level of preferences without having been able to evaluate the effectiveness of a previously acquired species.

Cultural Gaps and Personal Relationships

Personal relationships are key in the scaling of technologies (insofar as they allow or hinder the interaction of various agents and entities, the continuation of projects and their follow-up); they prevent or facilitate access to information and resources and at the same time chain inter-institutional relations to the personal sphere. Expedited and transparent interpersonal relationships facilitate scientific praxis, while rivalries, budgetary struggles, and fragile ties hinder the viability of a given project. The interviews carried out shed important light in this regard, where testimonies or narratives such as "our relationship was not good" or "relations between institutions depend on those who work in it" were a constant that allowed us to elucidate the importance of assertive interpersonal relationships for the development, achievement and continuity of research projects and initiatives that, by default, affect the processes of diffusion and adoption of agricultural technologies.

Weakness of Extension Processes in the Promotion of Forage Technologies

The neoliberal reforms of the 1990s (e.g., protectionist and decentralization policies at municipal and departmental levels) also weakened the key components of the national technical assistance system, which led to its progressive exhaustion and disarticulation. The lack of permanent updating in knowledge, methodologies, and technologies is highlighted in the UMATAS (Municipal Units of Agricultural Technical Assistance), and later, in the CPGA (Provincial Centers of Agribusiness Management) and EPSAGROS (Providers of Agricultural Technical Assistance Services). This has generated a knowledge gap between the generation of technologies and demanding users. In addition, the creation of EPSAGRO led to the attraction of resources and to the detriment of the quality of the service provided. To this is added that the service has focused primarily on agricultural issues, leaving aside the components of livestock development. All of the above is reflected in an institutionally weakened extension system where access to information, particularly on livestock technology issues, is seen as an important bottleneck.

Traditionally, Credit Lines Have Not Promoted Investment in Sustainable Intensification Systems

The actors recognize the importance that credit has had for agricultural development in the country, however, they highlight key bottlenecks associated with the low provision of credit in rural areas, information asymmetries that mainly affect small producers, and credit orientation rather toward productivity than sustainability. Despite the fact that the Fund for the Financing of the Agricultural Sector (FINAGRO) has established Special Credit Lines (LEC) for the promotion and renovation of pastures, as well as productive intensification through silvo-pastoral systems (e.g., Colombia Siembra, Livestock Sustainability), a pronounced effect has not been observed in the application of these lines, as the credits for livestock are mainly oriented to the purchase of animals. This has been accentuated as a consequence of credit dynamics such as growth in the substitute portfolio, where resources have been directed toward links in the chain with less risk than toward small producers (e.g., transformation

and commercialization). The previous dynamics suggest that the spirit of agricultural credit is being lost, as it works more to attenuate the asymmetries and inequalities between the actors of the Colombian rurality. However, it is important to note that, in recent years, credit institutions have established mechanisms for adoption such as the Rural Capitalization Incentive (ICR), whose objective is to help subsidize up to 40% of the debt of small producers that request credits for the establishment of silvopastoral systems.

The aforementioned issue clearly indicates, in the voice of some of the main agents and historical moments that play a role in the processes of diffusion and adoption of forage technologies, the difficulties that persist and hinder the way of a sustained and successful technification. Despite the many advances obtained in the matter and the valuable and decisive work of research institutions, there is still a long way to go, not only in the transformation of livestock landscapes in Colombia and the efficient implementation of improved pastures, but also in the understanding and study of agricultural innovation systems as historical processes, contingent, subject to change, and deeply affected by inter-actoral relationships. In closing, here are some possible insights on how these R&D processes can be refined.

DISCUSSION

Although mapping the interactions and dialoguing with key agents allowed the identification of the main actors and their interactions in the research and dissemination of forages in Colombia evidence important findings that we explain in detail, trends in academic literature show the changing historicity of R&D of agricultural technologies, its challenges and opportunities and the complex nature of inter-actoral relations and the contexts under which it takes place. This discussion is then framed taking into account these three key elements. We first address the historical context and the main transformations of the AIS. Next, we delve into the conceptualization of inter-actoral relations and their importance within the AIS, and lastly, we discuss the main bottlenecks found to be key in the AIS in Colombia.

Investments in agricultural research have had important changes over time with relevant effects affecting the development of research processes. For example, in the case of the CGIAR, research funding has changed dramatically: it went from being historically constituted in the long-term and directed through central institutions that were in charge of coordinating and managing projects, to being based on short- and medium-term programs, oriented to smaller projects, and of less scope. The mode of financing has also been significantly transformed, moving from unrestricted institutional allocations to concrete projects with concrete deadlines and strict budgets (Beintema and Echeverría, 2020). In turn, the thematic focus of the research has expanded significantly, with much more emphasis on politics, the environment, and biodiversity conservation (Beintema and Echeverría, 2020).

Both research and extension components have been oriented more toward the direct involvement of the producers in the identification of their demands, making rural subjects participants of their own transformation (Ardila, 2010). This has been due to theoretical transformations and methodologies on how to think, intervene, and transform rural livelihoods, a trend that has been growing since the late 1990s known as participatory research (World Bank, 2012). In the case of the CGIAR, the budget (in inflation-adjusted terms) remained fairly flat between 1980 and 2000, even though its mandate was broadened to cover a wide range of research topics. As a result, the continued search for sustained funding for public agricultural research at the global and national levels remains one of the main challenges (Beintema and Echeverría, 2020). The data indicate that, in general, the participation of the private sector in agricultural research in Latin American countries has been increasing over time, and currently it is private companies that supply most of the seeds and animal genetics to farmers in the region (Stads and Beintema, 2009).

Regarding one of our main findings, which is the explicitness that most of the intra-actoral exchanges registered are weak, unidirectional and without feedback loops, several authors refer to the existence of weak links between national agricultural research institutions and rural extension actors in most developing economies (e.g., Anderson, 2004). It is noted that the information used by extension institutions is not necessarily accurate or generated by research institutions, and research priorities do not necessarily align with the needs of extension institutions. Also, on many occasions both types of organization compete for resources (Anderson, 2004). A study carried out by FAO/BID (2016) illustrates this problem. This study evaluated the technical assistance service in South America. For the case of Colombia, 117 surveys were applied to service providers and 38 to producers. According to the results, 38% of the organizations stated that they had weak ties with other organizations, 30% had moderate ties, and 20% had close ties (11% did not respond). The strongest links are with local government agencies and banks and microcredit institutions (31%). In the case of Colombia, a manifested weakness is evident in the relationship between the organizations that provide technical assistance (UMATA, EPSAGRO, NGOs, or unions) and the organizations that can contribute to the provision of the service. For example, the link between research centers and UMATA and EPSAGRO was considered by 50% as weak, and only 43% of the unions consider it strong (FAO/BID, 2016).

Thus, a key to improving rural extension is the articulation between the actors that provide technical assistance services with the research actors, and so is strengthening of their capacities (Garrido-Rubiano et al., 2021). Therefore, one of the greatest challenges is to achieve coordination between the actors (Garrido-Rubiano et al., 2021). Problems related to weak links and lack of trust between actors, as well as asymmetries in communication between them, are recognized as factors commonly mentioned in the literature that uses the AIS approach to examine the problems of adoption of agricultural technologies (e.g., Spielman et al., 2011; Kebebe, 2018).

Although there is a historical presence of national and international institutions promoting research and innovation in agricultural technologies (forages for the example that concerns us here), we find that the assertiveness of interpersonal links has

determined immensely the adoption processes. For example, in this case-study, CIAT plays a leading role in the development of new and improved technologies for the country. However, the prominence of institutions has not translated into a higher adoption rate or a more expeditious path toward the goal, insofar as, as mentioned above, personal relationships directly influence inter-institutional ones.

Literature on this subject defines how the domain of intermediaries and/or bridging institutions (e.g., extension services that facilitate the transfer of knowledge and information between domains) is essential in the case of a successful AIS, which for the Colombian context, as mentioned, is in deficit. Thus, new technologies resulting from R&D processes in the agricultural sector have improved the quantity and quality of production and, therefore, have contributed to economic development, agricultural development, and poverty reduction in Latin America (Stads and Beintema, 2009). However, properly designed national agricultural research systems and adequate levels of investment are important prerequisites for agricultural development, food security and poverty reduction in all countries in the region (Stads and Beintema, 2009). Some recent research indicates that problems at the institutional and policy levels explain the low adoption of technology by small producers more than aspects of the producer (e.g., Birner and Resnick, 2010; Schut et al., 2016).

Widely discussed bottlenecks, such as extensive livestock farming, reductions in research budgets, weakness of the extension processes in the promotion of forage technologies, the low impact of agricultural credit lines, scarce articulation between R&D institutions and seed companies, as well as unpredictable speculation in the Brazilian seed market, have largely affected the Colombian context. First, the extensive nature of livestock can be explained here from structural conditions that discourage sustainable intensification, since in many cases, it is more efficient to acquire more land than to intensify. Low land prices, as well as the predominance of a fragile state to control access to it, have played a decisive role. Thus, structural factors that affect extensive livestock are (i) the higher profitability associated with new forage technologies that could lead producers to increase their herd size and hence the pasture area (Kaimowitz and Angelsen, 2008), and (ii) low land prices in many regions (e.g., Orinoquia) that make acquiring new land more efficient than intensifying existing land (White et al., 2001). Likewise, profitable technologies can also provide farmers with the additional capital they need to finance livestock expansion (Kaimowitz and Angelsen, 2008). Thus, if one of the main reasons for planting pastures is to have secure land tenure, the forest conversion to pasture can (and will) continue (Kaimowitz and Angelsen, 2008). This can be favored by price speculation processes, where acquiring more land would increase capital gains (Smith et al., 1997; Van Ausdal, 2012; Gutiérrez-Sanín and Vargas, 2017; Ponce de León-Calero, 2019).

In the research component, budget reductions experienced during the 1990s were decisive. Different reports of the ASTI (Indicators of Agricultural Science and Technology) (Stads and Beintema, 2009; Stads et al., 2016) evaluate trends in R&D in Latin America, pointing out the reduction of resources in all countries of the region in the 1980s and 1990's. These reports highlight direct effects of this reduction in research centers, such as the elimination of several long-standing research programs, and the deterioration of facilities and laboratories. Similarly, changes in the financing model since the 1990s (from long-term to short-term projects) and the constant struggle to obtain resources affected institutions such as the CGIAR, which in turn transformed the way of doing research and research and duration and impact of the projects themselves (Beintema and Echeverría, 2020).

In Colombia, the most relevant reform associated with technical assistance services was related to the State's decentralization processes, through which the National Government delegated the provision of this service to the territories. However, the limited capacity of the municipalities to assume obligations of such magnitude was not considered. Most local governments did not have the required capacities, the necessary administrative procedures, the external financing mechanisms, or the sufficient skills for the investment project management process (such as planning, monitoring, and evaluation) (FAO/BID, 2016). According to the National Agricultural Census (DANE, 2014), only 16.5% of the producers have access to extension services. Thus, among the bottlenecks identified in the technical assistance service in the country are the lack of capacities installed in the regions, the institutional disarticulation among those who generate, disseminate and accumulate knowledge, the low levels of associativity of producers, the loss of confidence of the latter in the effectiveness of the service, and a deficient monitoring and evaluation system (Hurtado et al., 2020).

Another element worth bringing to the discussion is that of credit lines. Although actors recognize the importance of credit for agricultural development in the country, they also highlight key bottlenecks associated with the low provision of credit in rural areas, asymmetries in access to information that mainly affect small producers, and a credit orientation more geared toward productivity than toward sustainability. Different studies have found empirical evidence where access to credit has a positive and significant effect on the adoption of new technologies and practices in the livestock sector (e.g., Lapar and Ehui, 2004; Turinawe et al., 2012). According to DNP calculations (2015), FINAGRO condition credits only reach 38% of the rural producers in Colombia, and credit lines have been directed toward profitability instead of sustainability in the livestock sector. According to FINAGRO's accountability figures (FINAGRO, 2020), credit applications from the livestock sector at the national level have been mainly channeled toward the purchase of animals, machinery, or the payment of the labor force, while credit applications designed to promote sustainable intensification systems, such as pasture renewal or the establishment of silvopastoral systems, have been very limited. This orientation is more pronounced in small and medium producers with participation percentages of 96.5 and 75.75%, respectively. For its part, the investment dedicated to sowing forages does not exceed 2% (FINAGRO, 2020). The advance of the substitute portfolio constitutes a problem in the accentuation of inequalities in the rural sector: despite the fact that the

resources for agricultural credit lines have increased over time, the majority of resources have been directed toward other links in the value chain with a lower level of risk. Regarding total credit by type of producer, there has been a decrease in the share of credit granted to small producers, and an increase for large producers. While in 2010 small producers participated with 26% of total credit, for 2019 this percentage was 23% (FINAGRO, 2020). For their part, the large producers in 2010 participated with 28%, while in 2019 this participation increased to 59% (FINAGRO, 2020).

Besides this, a poor coordination between national R&D institutions and seed companies is also profoundly telling. As institutions of diverse nature, both have different goals, and in many opportunities the release of materials is carried out without being able to guarantee the availability of seed at a commercial level. To illustrate, materials such as *Andropogon gayanus* cv. Carimagua 1, *Brachiaria dictyoneura* cv. Llanero, and *Brachiaria brizantha* cv. La Libertad, released by ICA (now AGROSAVIA) in the 1980s, failed despite promotional efforts due to the lack of basic and commercial seed supply (Ferguson, 1993). The low articulation between research institutions and seed companies was a priority issue during the workshops carried out by the International Network for Tropical Pasture Evaluation (RIEPT for its acronym in Spanish) (Ferguson, 1993), which denotes that the research sector identified a poor relationship with seed companies as one of the great obstacles to generating an impact on the adoption of improved forages.

Finally, speculation in the Brazilian market stands as one of the main bottlenecks, applicable to the Colombian case due to its high dependence on market conditions in the neighboring country. According to Legiscomex (2020), of the total imported seed in Colombia, more than 90% comes from Brazil, from where varieties mainly of the *Brachiaria* and *Panicum* species are imported. Forage seed production began in Colombia in the 1970s, a period in which seed production and marketing companies emerged (Ferguson, 1993). At this time, companies such as Semillano Ltda. directly produced seed in the company of farmers and in their own lots for varieties such as *B. decumbens*, *B. dyctionerura*, *Stylosanthes capitata,* and *Arachis pintoi*. Only a small amount of seed was imported from Brazil to meet the demand. However, the forage seed industry in Brazil took an important advantage. This was mainly favored by the environmental conditions that are particularly conducive to seed production, such as the altitudinal level that allows longer periods of light and, therefore, greater flowering and better synchronization (Hopkinson, 1981). These comparative advantages allowed the Brazilian industry to specialize and become one of the most important producers, consumers, and exporters of forage seed worldwide.

CONCLUSIONS

By way of conclusion, we highlight firstly and as a constitutive and conclusive element of this research, the importance of institutional alliances as a cross-cutting element in the adoption of agricultural technologies. We believe that, in addition to the relationships between institutions, it is urgent to promote greater communication and exchange between them, though research, dissemination platforms in which they present results, trends, and research proposals (future and ongoing). The temporary exchange of personnel, as well as guided visits between entities, could play vital roles in strengthening ties, increasing bonds of trust and maintaining this symbiosis over time. We also consider it essential to promote articulation between research and dissemination institutions and distributors of improved seeds, companies, and actors that are part of sustainable livestock strategies (e.g., Sustainable Livestock Table Colombia, zero deforestation agreements) in order to improve the dissemination and opening channels of communication between them, establishing dialogues that facilitate the development of public policies for the sector and contributing to the development of institutional and field capacities. Likewise, and as far as "third parties" are concerned, we maintain that it is of the utmost importance to take advantage of the potential of the milk processing industries to reach the primary producer: the direct link that has been created between these companies and producing communities can be useful for disseminating technologies through training and education programs. Since companies do not have the technical knowledge related to forage management, it is important to promote projects in association with research and extension institutions.

Solid relationships with policy makers, in which the benefits (economic, productive, competitive, and environmental) that the country has from promoting plans and projects that contribute to the implementation of forage technologies in Colombia is also a necessity for the sector. The involvement of public institutions with private actors in the development of technologies should be established in the agendas, not only of universities and research centers, but also between them and government agencies. Said dialogues could be aimed at consolidating strategies that allow the articulation at municipal, departmental, and national levels of each of the local initiatives where the nascent extension system can play an important role. It is well-known in academic literature that producer cooperatives and associations are fundamental actors in technology diffusion processes. Here, we propose to encourage the creation of these institutions in territories where they do not yet exist or in territories where existing ones are located far away from the producers. This can be done during vaccination periods or during technical visits by control bodies (e.g., ICA). It is also useful to point out that, in those consolidated associations, the sharing of experiences and cultural practices in the management of pastures and properties is encouraged. Together with extension agents, knowledge about scientific innovations can be addressed, thus generating fertile and lasting exchanges.

Through the creation of innovation networks (such as the Forages Network between CIAT and Agrosavia), alliances between research institutes, higher training centers, rural extension services, and producer associations can also be fostered in order to advance faster in technology adoption processes. Another possibility for improvement and transformation of the R&D system lies in the promotion of incentives for adoption. The creation of credit instruments for the adoption of technologies

and the articulation of agricultural credit lines with extension services, can positively transform the panorama in terms of the adoption of improved forages. This is important not only for forage technologies but also for silvopastoral systems, which tend to be long-term investments as well.

Finally, the strengthening and prioritization of livestock production chains in the Departmental Agricultural Extension Plans (PDEA) in those territories where livestock predominates and there are high levels of deforestation and low adoption of forage technologies is a fundamental and unquestionable axis. The training that is established for this purpose should not only involve the management of pastures and forages; For success to be sustainable over time, we are convinced, extension strategies must include a holistic campaign in which producers are interested in the effective use of support information, social appropriation of knowledge, and problem solving, mainly through open or collaborative innovation, participatory research, and the use of Information and Communication Technologies.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics Committee of the Alliance of Bioversity International and CIAT. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

NT, KE, MD, and SB: conceptualization, methodology, writing the original draft and review and editing, and resources. NT, KE, and MD: formal analysis. SB: supervision, funding acquisition, and project administration. All authors contributed to the article and approved the submitted version.

FUNDING

This work was funded by the CGIAR Research Program on Livestock. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

ACKNOWLEDGMENTS

This work was carried out as part of the CGIAR Research Program on Livestock. We thank all donors who globally support our work through their contributions to the CGIAR System.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2021.741057/full#supplementary-material

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