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Agricultural Innovation as a Determinant of a Sustainable Transition in Rural Territories: Evidence from Costa Rica

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Abstract

The predominant economic activities in rural territories are agriculture, tourism, and ecosystem services, with agriculture being the predominant one. The agricultural sector faces several critics regarding its sustainability and structural difficulties for innovation. Yet, some innovations in line with bioeconomy and the use of digital technologies in agriculture have potential to reconcile economic and environmental goals. Therefore, this research aims to determine the contribution of innovations in the agricultural sector to the sustainable transformation of rural territories in Costa Rica. This is achieved using a case study methodology, covering cases representative of more than 95% of the agriculture production of the country. Finding that these trends of innovation can foster the sustainability of the sector and rural territories while improving economic outcomes; that the biggest impact of these innovations is when the two trends, digital technologies and bioeconomy, are combined; and that the forms of governance play a paramount role in the democratization of innovation, especially for medium and small-sized producers, and in their diffusion within the territory.

Keywords: agriculture, innovation, economic and social development, governance, sustainable development, bioeconomy, digitalization of agriculture, rural development

1. Introduction

Rural territories face disparities and socioeconomic gaps in terms of poverty and development in general, and in Costa Rica in particular (Rodríguez-Soto, 2024). While its main economic activities are ecosystem services, tourism, and agriculture (French, 2022), which face challenges in terms of production and environmental impacts. In these territories, agricultural activities continue to be the predominant ones, since they generate most of the employment in rural territories. However, their contribution in terms of added value is low, which reveals something about the geography of wealth.

Since the agricultural sector is the core of rural economies and the main generator of employment in them, its problems go beyond the generation of value; it is a matter of territorial development. Furthermore, agricultural practices have not always been sustainable, as is remembered by the "green revolution", with its intensive use of chemical inputs and degradation of nature. The impacts of these practices include soil erosion, water pollution, a decrease in biodiversity, an increase in food toxicity, health issues for the rural population, and the impoverishment of low-income producers (Chávez, 2019).

On the other hand, there is the contribution that the agricultural activities make to ecosystem services, such as carbon capture and biological corridors (Hernández, 2020). Due to this, this research aims to determine the contribution of innovations in the agricultural sector to the sustainable transformation of rural territories in Costa Rica. Because it is a sector characterized by strong contrasts in the country, in which various actors are involved and is organized in different forms of governance, from collaborative ones to large private firms.

Currently, innovations in this sector are driven by two main streams: digital technologies and bioeconomy (Goulet, et al., 2019; Segura et al., 2023). Both have the potential to reconcile economic and environmental goals, but this relationship is still uncertain (Segura et al., 2023). To delve deeper into it, a qualitative research approach is proposed, with a methodological design of case studies (Yin, 2003), to collect evidence that confirms or disproves the proposed hypothesis: that those technological innovations can contribute to the efficiency and sustainability of the agricultural sector. Finding that, indeed, these streams of innovation have the potential to improve the

relationships between social systems and ecosystems in various areas of incidence, particularly those identified as having negative impacts with the practices of the green revolution. While recognizing that these are the direct effects, other indirect ones need to be addressed in future research.

2. Methodology

When working with qualitative approaches, the research design and analysis must be present across the whole process, from theory and categorical construction to the recollection and analysis of data (Schettini and Cortazzo, 2015; Yin, 2003). Because the phenomena are incommensurable in their qualitative aspects, it is not possible to capture the entirety of them. Therefore, the data collected will depend on the delimitations, definitions, and instruments. Consequently, it is necessary to articulate three categorical levels to maintain the consistency of research for these approaches: theoretical categories, analytical categories, and a systematic coding process that mediates between them (Schettini and Cortazzo, 2015).

The soundness of the conclusions and generalizations that can be reached lies in the interconnections of these categorical levels. It is mandatory to make a clarification in regard to the nature of qualitative work: as it is not based on probabilistic sampling, it is not possible to reach generalizations about universes or populations (Yin, 2003). The nature of the generalizations enabled by qualitative approaches is analytical, which allows supporting, modifying, or questioning the starting theoretical assumptions and hypotheses through the evidence provided by the data (Yin, 2003).

Thus, this research begins with an exhaustive review of literature on the two streams of innovation identified as key for the agricultural sector and the rural world: bioeconomy and digitalization. To do this, a search was carried out in academic databases (Emerald, Scopus, ProQuest) and specialized search engines (Google Scholar and the Institutional Repository of the National University of Costa Rica). Departing from keywords such as innovation, innovation systems, sustainable development, bioeconomy, and digitalization of agriculture.

It was decided to follow Yin's (2003) approach to case study design since it empowers the use of data of various natures and sources, strengthening the conclusions of the analysis. Also, because the goal is to determine the contribution of innovations in the agricultural sector to the sustainable transformation of rural territories in Costa Rica, for that reason a multiple-integrated case study design is applied. This type of design addresses several cases from a perspective that seeks to identify the operational details of the interactions between the dissipative units of the phenomenon. Furthermore, this approach is of positivist leaning, which makes it better suited for generalizations. Figure 1 summarizes the research design.

Now, since it is desired to reach conclusions of national scope, it is paramount to cover the main economic activities in the agricultural sector. Thus, in this research, we worked with the main four agricultural products to the country: coffee, bananas, oil palm, and sugar cane, which together represent 95.2% of national production (SEPSA, 2022); and with cattle ranching, the main livestock activity in Costa Rica, occupying 28.5% of the agricultural parcels of the country (Hernández, 2020).

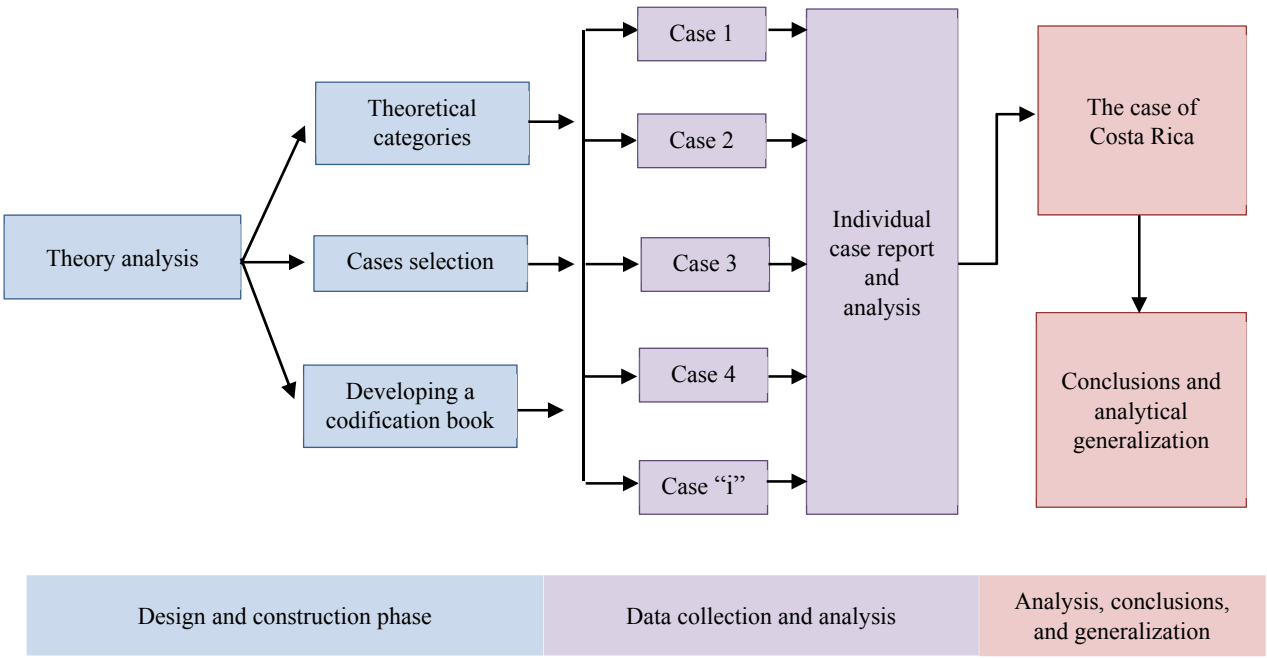

Figure 1. Methodological design

Source: Own elaboration, based on Yin (2003).

3. Theoretical Framework

The theoretical framework will be divided into three subsections. One will focus on innovation and a brief overview of the approach of systems of innovation. The second one will summarize the ideas regarding the bioeconomy and its relations to sustainable development, and finally, a third one will be dedicated to the digitalization of agriculture and its contributions to sustainability. But before proceeding, to appreciate the possible benefits that derive from these innovation drivers, it is necessary to present some introductory considerations around the Green Revolution of agriculture of the last century.

The Green Revolution is a term used to refer to a period of industrialization and a dramatic increase in the productivity of agricultural activities through the use of agrochemicals. Even though productivity increased significantly, it came at the price of great environmental and public health hazards (Chaves, 2019). On one hand, the use of chemicals had harmful effects on the local biodiversity; at the same time, these agrochemicals pollute water sources and the earth. All this while the increase in productivity and demand stimulated an expansion of production, which led to deforestation and soil erosion.

On the other hand, several problems regarding public health and social development arose. First, the use of agrochemicals that enhance productivity provoked an increase in the toxicity of the food and its derivatives, which were ingested by the population. A second and closely related issue appeared at the local level, since the use of agrochemicals was a hazard in itself for the rural population and plantation workers that were in contact with the chemicals. Finally, another concern of social nature came into scene because the chemicals weren't available for everyone, enlarging the breaches in productivity between small, medium, and big producers.

In summary, the effects of the Green Revolution can be listed as follows (Chaves, 2019): soil erosion, contamination of water, decrease in biodiversity, increase in food toxicity, health issues for the rural population, and impoverishment of low-income producers.

3.1 Innovation and Systems of Innovation

Innovation is understood as the introduction of a novelty of social relevance (Segura et al., 2023). These novelties can be new technologies (technology), new ways of combining existing ones (technique), forms of organization, ways of relating to ecosystems, or behaviors. The specifics don't matter that much, but it is mandatory that the novelties have a social and collective character to be considered innovations. This is the main difference between an innovation in the colloquial sense of the word and its concept in the social sciences. Innovations are transformative changes in social dynamics, not just something new; no matter how novel an idea may be, it is not

classified as innovation if it occurs in isolation.

Therefore, to comprehend the concept and its potential, it is necessary to associate it with social dynamics and development. The relationship is obvious since it deals with techno-productive changes, which express social relations. Also, innovation is sometimes thought of as a potential response to the search for sustainable solutions to pre-existing problems because it enables new ways of doing things. Despite this, there isn't a direct and linear connection between these concepts. Not all innovations are sustainable or advantageous in terms of their socio-ecological implications, and maybe others are ecologically sustainable but economically unviable.

Now, this perspective of innovation as a process that transforms dynamics demands it to be contextualized. Innovations occur within the complex network of social, economic, cultural, historical, and environmental interconnections that frame a society. These complexities have led to the development of theoretical bodies that seek to understand innovation in this intricate system of relationships. This is how the term innovation systems arises, whose main promoter is Lundvall (2002). Its core proposition is to understand innovation as a systemic phenomenon, subjected to path dependency, with implications for the system as a whole (Orozco, 2017).

The most frequent delimitation is that of national systems of innovation (Edquist, 2012, 2013; Lundvall, 2002; Segura, et al., 2023), although they can be characterized at sectoral or territorial specifications (Segura et al., 2023). Initially, the concept of a national system of innovation emerged to reflect the scope of a government's policy incidence and how the variations between countries affect the proliferation of innovations, their effects, and impacts (Segura et al., 2023). Additionally, it is a useful division to carry out case studies and compare the effects of policies and policy tools, since different countries implement different policy combinations and obtain distinct results.

But considering a country in aggregate may fall short to understand innovation; not every policy or instrument affects all sectors or territories (Segura et al., 2023). This led to the appearance of denominations of sectorial and territorial systems of innovation (Segura et al., 2023). In the case of the sectorial denomination, it is a national specification by sector; it includes the same elements that are contemplated at a national scale, but by their impact on a particular sector. At the same time, this narrows the list of relevant actors to those directly involved in the sector, as well as the institutional and political frames. It is a delimitation of the scope of the analysis.

In the case of territorial systems of innovation, it corresponds to a change in the unit of analysis, from the nation to the locality or territory (Segura et al., 2023). Although this concept contains several particularities, it must be understood as a subsystem in continuous interrelation with the system and other subsystems (Segura et al., 2023). Also, when analyzing systems innovation from a local perspective, tacit knowledge becomes paramount (Berdegué et al., 2011; Salom, 2003; Segura et al., 2023). The territorial systems innovation are axial to comprehend the development processes of territories; in fact, innovative social coalitions are considered key to solving development trade-offs and overcoming asymmetries (Berdegué et al., 2011).

3.2 Bioeconomy and Sustainability

There is no consensus regarding a univocal definition for bioeconomy (Segura et al., 2023). Despite the lack of an agreement on a single definition, the popularity of the concept is undeniable, mostly because of its capabilities to joint environmental and economic goals, at least in theory. Although it is possible to identify routes that arise from practical experiences and academic discussions (Segura et al., 2023). By analyzing the literature, three approaches to bioeconomy can be identified: a line of biotechnology, another of bio-resources and, finally, one of bio-ecology (Bugge et al., 2016; Dietz et al., 2018; Pfau et al., 2014; Segura et al., 2023). Of these, the first two account for most of the publications and occupy prominent spaces in political agendas.

Before proceeding, it is important to clarify that the identified currents are a categorical distinction to highlight certain elements at an analytical level, yet, this separation is artificial. In practice, every initiative tends to present a mix of all these characteristics. The line with a focus on biotechnology is centered on advance research and product development, aimed at the markets. In the trend of bio-resources, the emphasis is on the use of biomass and the circularity of the productive processes, while keeping an eye on generating additional value. At last, the leaning of bio-ecology is more interested in modifying the relations between societies and local ecosystems, preoccupied with concerns of sustainability, and to make the most out of the local biodiversity and ecosystem services.

A generic all-encompassing definition for bioeconomy could be the economy based on biology and biosciences, which depends on biological resources, their functioning, or principles (Segura et al., 2023). From this conception, it is easy to see how bioeconomy is a driver for innovation in the agricultural sector. To begin with, agriculture is biomass production by itself, which puts it within the classification of bioeconomy. Second, nowadays, the

bioeconomy is proposing a new techno-productive paradigm by changing the material base of society from hydrocarbon to carbohydrates (Rojas, 2023), highlighting the importance of biomass-producing activities. Third, the transition from the use of agrochemicals and chemical inputs to biochemicals and inputs.

These drivers of innovation have important impacts in the agricultural sector. To begin with, biotechnology offers possibilities to enhance seeds and plants and develop new bio-inputs that can fulfill the role of agrochemicals while lessening the environmental impacts. It is possible to think of a lot of sub-products of agricultural production, as abundant quantities of biomass are not fully utilized in many productions. Also, there are numerous possibilities for a better integration of the agricultural productions into the ecosystems; agriculture itself provides ecosystem services, but an ecological or regenerative design of production can lead to better results. Finally, the new strategic importance of biomass and bio-resources can empower rural development, as rural territories are their main producers.

3.3 The Digitalization of Agriculture and Sustainability

The digital economy is a phase of the economic system characterized by markets based on information, communication, technological industries, and moving socioeconomic relations to digital environments (Ulezko et al., 2019). The term digitalization of agriculture refers to the applications of digital technologies to agricultural productions. Just like bioeconomy, it is a recent trend, so there isn't unanimity in the definitions, as digital technologies are a broad category. A comprehensive definition would be that the digitalization of agriculture is the expression of the digital economy in the agricultural sector.

Following this reasoning, the digitalization of agriculture is the transformation process in the agricultural sector in all the senses and aspects contemplated by the digital economy. The digital transformation implies new business models, immersed in digital ecosystems where the definitions of information infrastructure, security, skills, and competitiveness change. Some consider it an inevitable structural change (Ulezko et al., 2019), others a progressive search for solutions to certain challenges (Kuzmich, 2021), or a way to optimize and stabilize production (Vorobeva et al., 2021). In general terms, it is the application of digital technologies in the agricultural sector, be it in productive systems, value chains, or food systems (Klerkx et al., 2019).

Digitalization can improve the stability and efficiency of production systems (Vorobeva et al., 2021). First, technologies can make "smart farms", optimizing productivity by improving working times and costs (Vorobeva et al., 2021). Second, digital technologies allow the improvement of agricultural information systems to obtain deep real-time information (Klerkx et al., 2019). Together, these applications lead to the term precision agriculture (Klerkx et al., 2019), which has great potential to increase the sustainability of production and promote better decision-making and risk management. Additionally, technologies can improve the registry and control of the ecosystem services provided by agricultural productions, of strategic importance to the relations between rural and urban areas.

Another way in which digital solutions can improve agricultural value chains is in the coordination of supply and demand in food markets, due to the rapid and accurate flow of information (Klerkx et al., 2019; Kuzmich, 2021). In addition, technologies create spaces for exchanges, bringing production and consumption closer (Klerkx et al., 2019). This is of paramount relevance since agricultural value chains have many producers and consumers but a few intermediaries (processing and packaging) that capture much of the value (Jiménez, 2011). Enabling the interaction between the stages of production and consumption can transform the dynamics and structure of the value chains, fostering economic inclusion and opportunities.

4. Results: Sustainable Innovations in the Agricultural Sector of Costa Rica

Sustainable rural innovation has not been deeply explored in Costa Rica, so, in this section, the cases of the main agricultural productions will be presented (coffee, bananas, oil palm, sugar cane, and cattle); later, the impacts of the innovations on sustainability will be systematized. To construct each case, several sources of information were used, including personal communications, deep interviews, field visits, and secondary information.

4.1 Coffee Production and Innovation in Costa Rica

The production of coffee in Costa Rica began in the 16th century, and since then it has consolidated as a paramount product in the country's development and history. Even in recent times, in 2020 coffee production represented 24% of the agricultural parcels of the country, being the second one in order of importance. Despite this, the production of coffee is facing various threats, like an unstable exchange rate between Costa Rica and its main buyers, environmental hazards, climate change and variability, and the proliferation of plagues. Figure 2 presents the geographical distribution of coffee production in the country.

When looking into the innovations in this production, it is possible to identify them in the two trends that were

addressed in the theoretical framework: bioeconomy and digitalization. In terms of bioeconomy, the innovations arise from one of the main issues with this production: the residual biomass. The main product of coffee are the beans, which leave around 80% of residual biomass (the peels and pulps), not to mention the issue regarding the leftover water from cleaning the coffee beans. In the face of these problems, most coffee producers' resort to bioeconomy-propelled innovations.

The most common approach is to transform the remaining biomass into bio-inputs to support production. Usually, coffee processors use the leftovers of the pulp and peels to create substrates, used for their seedbeds or as fertilizers. These solutions are frequent in collaborative organizations, where, once elaborated, the substrates are distributed among the members of the organization in proportion to their contributions or needs. Also, in the cooperative sector, there are several initiatives that imply complex processes and higher added value. For example, some use the peels and pulps to make coffee flour, beverages, and even nutritional supplements.

The issue with the water used in the processing stages is complicated, as it ends up with a lot of nutrients imbued in it. The difficulty arises from the effects of these nutrients on the local ecosystems if they were to be tossed in the rivers; a second concern appears because the biomass in the water decays and tends to smell bad, causing a public health issue for the local communities. To address these, coffee processors devised systems of oxidation lagoons, where bacteria decompose the nutrients and biomass in the water, lessening its ecological impacts and bad scent. Later, once treated, this water is return to the ecosystems.

In the case of digital technologies, they are mostly used for control, registry, and surveillance of production. For example, Costa Rica has a public institute dedicated to coffee, which provides the producers with platforms of information so they can be updated with innovation trends. This institute also has platforms for market and hydrometeorological risk management, where the producers can access market prices, weather forecasts, and early alerts on disasters. Aside from these public actions, private agents use technologies to have quicker and more complete information mechanisms while reducing costs. For example, the use of aerial and satellite photographs that reduce the need for mobilizing people and, therefore, the emissions and waiting times.

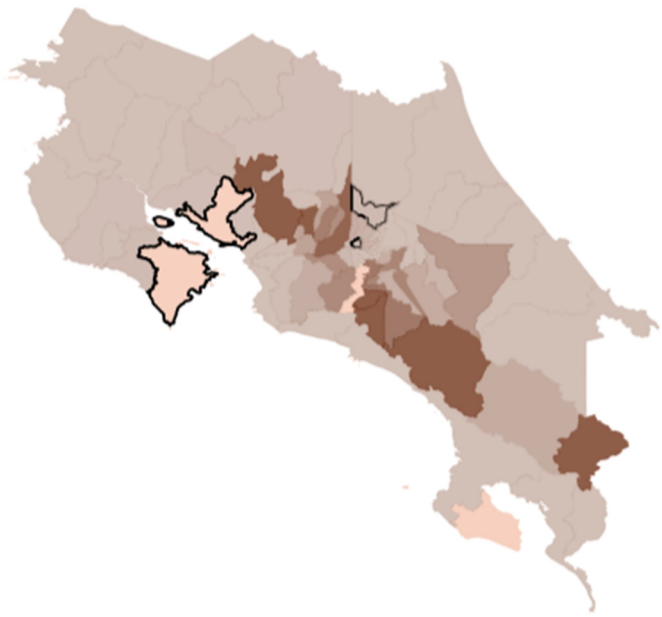

Figure 2. Geographical allocation of coffee production in Costa Rica

Source: Own elaboration with data from the Central Bank of Costa Rica.

Beside these basic uses, there is another initiative that it's mandatory to mention: Project One, from a cooperative named CopeDota. This project is directed toward the "future of the agricultural sector of Costa Rica" as they claim. They devised it by combining solutions from digital technologies and bioeconomy. It surged in the face of a decrease in the productivity of the plants. The cooperative initially believed that this decrease was due to the trees that are used for shadow. Yet they couldn't cut the trees, as some of them are protected by law and others are necessary for the ecological seals of the products, essential to keeping good market prices.

Due to this, the cooperative looked for assistance from the academy, and they discovered that the issues lay in the soil composition, not the trees, and so the project started. The project involves the same bioeconomy innovations mentioned for the whole sector but upgraded with the precision of digital technologies. They put soil sensors on each farm that give them soil analysis in almost real time. Then they combine this data with artificial intelligence to create substrates and fertilizers specific to the needs of each farm from the residual biomass. Also, they complement these fertilizers and substrates with captured emissions from their tractor. Right now, this project has proven to be a great success, as it not only restored the productive capabilities of the plants, but even duplicated the harvests.

4.2 Banana Production and Innovation in Costa Rica

Just like in the case of coffee, bananas are a product of great historical relevance for the country, particularly in the 19th and 20th centuries. The importance of this production is exceptional for the Atlantic Coast region; in the province of Limón banana production represents 76% of the local labor. Figure 3 shows the spatial concentration of banana production in the country.

Traditionally, banana production has presented several issues regarding sustainability and the use of agrochemicals. The most obvious one is the absorption of harmful substances in the products that are later eaten by humans or animals. Another relevant problem is the application of these substances, as it is commonly done with planes, which causes drag effects that damage the local ecosystems and compromise the health of the surrounding human settlements. All these led to numerous restrictions and regulations on the use of chemicals in this production that created a window of opportunity for green innovations.

In line with the bioeconomy, some innovations focus on the development and use of bio-inputs as substitutes for the traditional chemical substances that, in some cases, became illegal. On the other hand, in line with the use of digital technologies, there are various improvements to the productive processes that are worth mentioning. Initially, the application of substances is still mainly done with planes, but it has improved significantly with precision systems that automate the discharge and coordinate it with GPS signals.

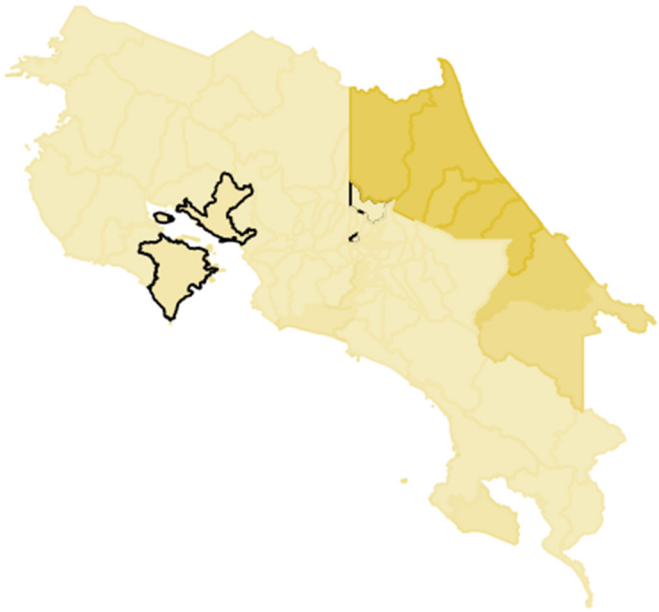

Figure 3. Geographical allocation of banana production in Costa Rica

Source: Own elaboration with data from the Central Bank of Costa Rica.

Even though planes are the main way to apply chemicals, several options have appeared, like helicopters and drones. It's important to highlight the trade-offs between these vehicles, as the more precise ones are more expensive. For example, planes offer the least precise application, with severe drag effects, but they can apply 140 hectares per hour, with a cost of approximately $7 per hectare; a helicopter can cover 90 hectares per hour, with a cost of $10-$15 per hectare; finally, a drone provides the most precise application but only covers 7 hectares per hour, with a cost of $30-$35 per hectare (these estimates were provided by Marco Jara, an agronomist with more

than 30 years working with banana).

Yet, the decision between them depends not only on cost-efficiency, because small farms or those located nearby population settlements have no option but to use drones or helicopters. The higher cost of drones can be explained by two factors. First, the charging capacity, because a drone cannot carry a heavy-duty tank, it needs to return to reload faster. Second, even if drones are highly advanced in some respects, they are still operated in the same way as planes or helicopters; they are not automated and need human pilots. This second point is probably something that will change with time.

Finally, as in the case of coffee, there is a public, non-state, institute that is dedicated to supporting the production of bananas. This institute offers several information platforms that producers can access to obtain information regarding better practices, hydrometeorological risks, market prices, etc. This institute also provides extension and research services to promote the diffusion of innovations.

4.3 Oil Palm and Innovation in Costa Rica

The oil palm is another key production for the rural territories of Costa Rica; this one is concentrated in the south part of the Pacific Coast; currently, the province of Puntarenas agglomerates the 87% of the production. This production has shown a dramatic increase in its added value, as it duplicated between 2019 and 2020 and then duplicated again between 2020 and 2021. The oil palm presents a peculiarity that makes it interesting to study when addressing agricultural products and economic rural development: its crop is continuous, so it provides a continuous stream of income. Figure 4 shows the geographical allocation of palm production in the country.

In the trend of bioeconomy innovations, in the case of oil palm, it is possible to identify the same transition from agrochemicals to bio-inputs. A second initiative that goes in line with bioeconomy is the implementation of biodigesters to transform the residual biomass from productive processes (to produce energy and fuels). Aside from that, the innovations powered by bioeconomy concentrate on the finished products, as there has been a transition in this production in Costa Rica, from selling raw materials to goods for consumption, or at least to add more value.

In the case of innovations powered by digital technologies, there are two to consider. The first one is related to the use of aerial and satellite photographs to maintain control and supervision of the production. Before, it was necessary to send teams to the field and check on the plantations; now this control can be done in a cheaper and faster way. At the same time, this allows to identify areas affected by harmful issues and apply localized treatments, for example, in case of a disease or need for water. Second, the digital technologies allow implementing precision applications of substances and irrigation with drones; the case of irrigation is particularly remarkable, as the hydrological footprint was reduced by 95%.

At last, as in the previous cases, Costa Rica has a public, non-state, institution dedicated to overseeing the production of oil palm, with analogous services to the previous ones.

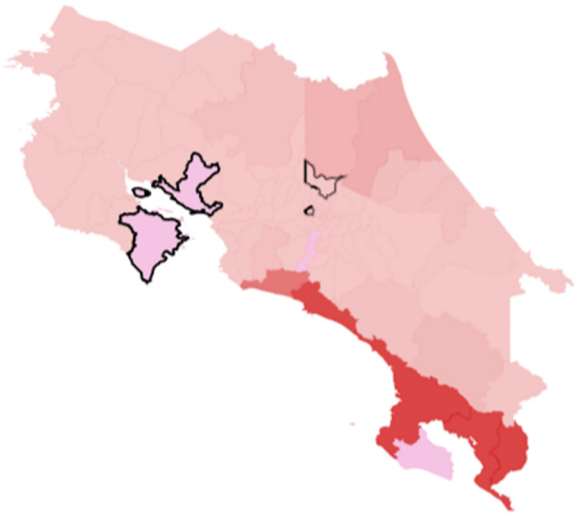

Figure 4. Geographical concentration of the production of oil palm in Costa Rica

Source: Own elaboration with data from the Central Bank of Costa Rica.

4.4 Sugar Cane Production and Innovation in Costa Rica

Sugar cane is yet another long-dated agricultural product in Costa Rica, introduced in the 16th century. Originally, it was directed toward domestic consumption, but recently it has been oriented toward external markets. Figure 8 shows the spatial distribution of the production of sugar cane in Costa Rica.

Regarding sustainability, on January 24 of 2024, LAICA (the Sugar Cane Industrial Agricultural League, by its Spanish syllabus) signed an agreement with the Ministry of Agriculture and Livestock that seeks to promote the sustainability of the sector through innovation, contemplating aspects such as bioeconomy and precision technologies. In addition to this, LAICA has the "Cultivo futuro" (Future of Cultivation) platform, which has information and training so that the participants of the sector can improve their practices with a view to sustainability. Along with support in additional aspects, like accounting and other types of assistance.

Despite numerous efforts, it was impossible to establish contact and carry out interviews or fieldwork for this production, so it is not possible to extend this section further.

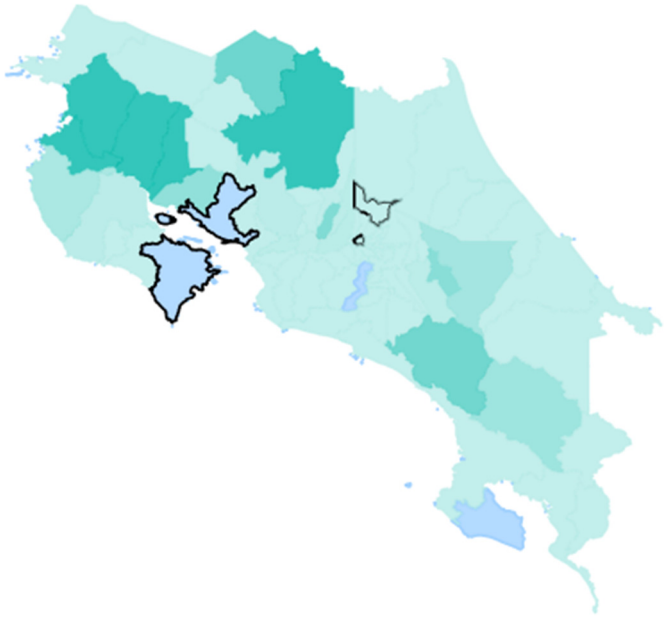

Figure 5. Geographical allocation of the sugar cane production in Costa Rica

Source: Own elaboration with data from the Central Bank of Costa Rica

4.5 Cattle and Innovation in Costa Rica

Cattle is a relevant economic activity for the country. It is present across the nation and is the activity that occupies the biggest number of farms in Costa Rica (28.5%). At the same time, it is important to notice that this activity is questioned worldwide for its environmental impacts and sustainability due to the emissions resulting from the excrement of the cows. Figure 6 shows the geographical distribution of cattle in the country. Despite the impression of concentration, this activity has presence in almost every county.

Regarding innovation, for this production, the applications are concentrated on the trend of digital technologies, with impacts that enter the denomination of bio-ecology. Recently, the country has imposed the obligation to keep a digital identification for each animal so it can be traced to have a better registry and control system. Another application of technology is used at the milking processes; now it is possible to substitute the traditional button panel of milking machines with digital consoles. These consoles allow building better databases and even automating some parts of the process.

A second level of application is implemented in the process of raising and keeping the animals. There are two methods that vary in their complexity, functions, and costs. The more expensive and technologically advanced one is the use of tracking collars with a receiving console. These collars track the activities of the cows, giving information on the health, location, and production of each animal continuously and in almost real time. While the base console creates databases and analytical reports to improve the productive process. The problem with this

technology is its cost, as it tends to be expensive (around $200 for each collar, and the console is even more expensive), making it inaccessible for small or even medium producers.

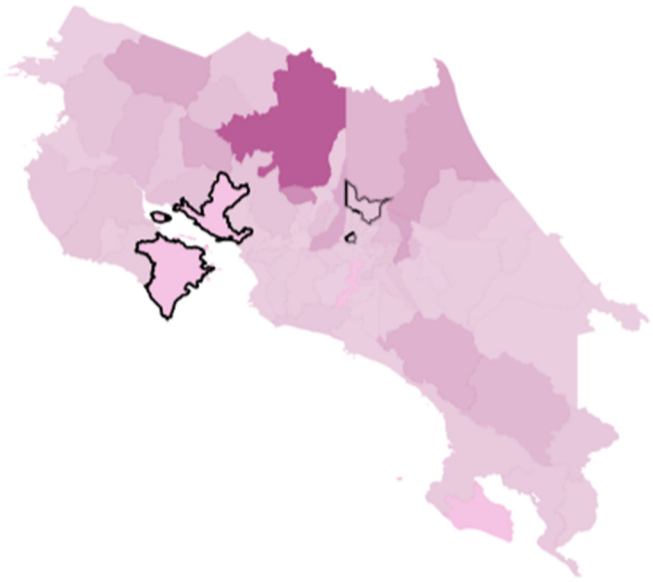

Figure 6. Spatial concentration of cattle in Costa Rica

Source: Own elaboration with data from the Central Bank of Costa Rica

A cheaper alternative to the collars is the use of mobile phone applications that systematize the information and keep track of the whole productive process. These applications aim to do a similar function as the collars and consoles, with the difference that the information is introduced manually to the apps by the workers of the farm. Then, from this information, the apps generate databases and analyze the production processes and each animal. At the same time, these apps support the implementation of regenerative designs in the production systems.

They keep track of the time the animals spend on each part of the farm and when to move them to another zone in order not to overpass the ecosystem's absorptive capacity of the residuals. With this information, the environmental impact of cattle is not only reduced, but it seems to be positive for the ecosystem, because the excrement acts as fertilizer if there is not an overcharge of it. These applications combine economic and environmental information to create a sustainable and economically viable business model for cattle, solving two major concerns in this industry, especially for small and medium-sized entrepreneurs.

5. Discussion: Agricultural Innovation Impacts on Sustainability and Efficiency

Despite the qualitative differences between the cases, they reveal interesting dynamics to this paper's hypothesis: of agricultural innovations having potential to promote, both, sustainability and efficiency in the agricultural sector.

In the case of coffee, there are several innovations powered by the bioeconomy, that are inspired by the biggest problem of coffee production: residual biomass. These innovations enhance the circularity of the productive process by a cascade use of the residual biomass and the creation of new products from it. At the same time, this has effects on the efficiency of the productive process, because most of the residual biomass is used to produce bio-inputs that increase the productivity while reducing the cost of buying them from external sellers. Another part of the residual biomass is dedicated to making other final products oriented to consumption, with higher added value. Even the residuals that cannot be converted into anything else (residual water) are treated before pouring them back into ecosystems.

Despite how advanced some of these bioeconomy innovations are, the reviewed cases show that the best results in terms of sustainability and productive efficiency come from the combination of digital technologies and bioeconomy. This was illustrated by the case of Project One, which managed to attain all the previous results and even more, like duplicating the harvests. Also, this project permitted the coffee production to keep the shadow

trees that would have been cut otherwise, which would have affected sustainability and selling prices due to the loss of ecological seals and certifications. All these innovations permit a better integration of the productive systems and the ecosystems, while increasing the value created from the biomass at the same time.

For the case of banana production, the innovations arise from a long-dated issue of this product: the need for agrochemicals. These chemicals cause a lot of hazards in terms of damage to ecosystems and threats to public health, mostly due to the dragging effects and high toxicity of the substances. To solve these problems, the producers' resort to solutions powered by bioeconomy and digital technologies. First, there is the development of bio-inputs and biodegradable substances to mitigate the toxicity of the traditional chemicals on the ecosystem.

Second, there was a significant improvement in the precision of the application, empowered by digital technologies; this managed to reduce the dragging effects. Also, technologies like drones enable the aerial application of substances in small parcels and those closer to residential areas with the minimum risk of dragging effects. Yet, these innovations require further analysis, as it was possible to identify a direct trade-off between cost and sustainability between the application vehicles. Not to mention that the most adequate application tool for small properties is the drone, which is the most expensive, and, clearly, smaller parcels tend to have smaller incomes. So, there is a chance of new exclusion dynamics that could increase the socioeconomic breaches, but, at the same time, these innovations can solve a public health issue of this production.

For the oil palm, it was possible to identify positive effects on sustainability derived from innovations. To begin with, this production used to be criticized due to the use of water. By implementing precision systems for irrigation, it was possible to reduce the hydrological footprint by 95%. These precision systems also allow reducing the application of substances and localizing them in the specific areas where they are needed. Also, they manage to replace traditional agrochemicals with bio-products. Both applications of technology have relevant effects on the hydrological footprint of this industry.

The oil palm industry in Costa Rica has evolved in their capabilities to use the biomass and add value to their products. There has been a steady and remarkable increase in the value generated by this industry. That was achieved by an expansion of the production and by selling processed products instead of raw materials. A second line of advancement is the implementation of biodigesters to transform the residual biomass into energy and the search for derivative products of it. In combination, these innovations can foster the sustainability and economic development of the sector and territories.

Finally, in the case of cattle raising, the innovations were mostly powered by digital technologies and aim to better integrate the productive system into the ecosystems, which can be considered a bio-ecology solution. Here, the improved information analysis helps to control the productive process and design it in a regenerative manner. This innovation achieves a solution to the biggest claim around the sustainability of cattle: the control and distribution of the excrement and its resulting emissions. Furthermore, this approach enhances the administrative abilities of the farmers, facilitating a more efficient economic management of their production.

Table 1. Synthesis of innovation impacts on sustainability on agriculture

Production	Coffee	Banana	Oil palm	Cattle
Innovations	*Development of bio-inputs. *Use of residual biomass. *Sensors to analyze soil. *Aerial photographs. *AI for fertilizers. *Support platforms.	*Use of bio-inputs. *Controlled application of chemicals. *Aerial images. *Support platforms.	*Increased circularity of the process. *Use of bio-inputs. *Controlled application of chemicals. *Aerial images. *Support platforms.	*Automated milking systems. *Registry and control. *Collars to keep check. *Applications for regenerative production.
Sustainability	*Improvement of bio-inputs. *Reduction of dumped waste (biomass) on ecosystems. *Better use of resources. *Increased circularity of the productive process. *Control of public health issues (bad smell).	*Reduction of side effects of application. *Reduce effect of chemicals on ecosystems. *Control of public health issues related the application and absorption of chemicals.	*Improvement of the control of chemical application. *Reduction of water use (95%). *Pest control in a localized manner, reducing impacts on local ecosystems.	*Well-being of the animals. *Less concentration of emissions from excrement. *Fertilize soils. *Better integration to ecosystems.
Economy	*Great increase of productivity (double in the case of Project One). *Cost reduction by producing bio-inputs. *Better prices due to ecological seals and certifications.	*Reduction of costs of application. *Better prices due to ecological seals and certifications.	*Better control of plants renewal. *Reduction of costs due precision applications and irrigation. *Better prices due to ecological seals and certifications.	*Improvement of economic control of production. *Visibility of economic costs, not only financial ones. *Better prices due to ecological seals and certifications.

Source: Own elaboration.

Table 2. Contribution of the innovations to the sustainability of rural territories

Impact areas	Type of technology	Contribution	Evidence
Soil erosion	* Soil censors. * Specifically design substrates with AI. * Early warning systems. * Aerial photographs. * Development of bio-inputs. * Residual biomass treatment and processing. * Regenerative design of productive systems.	* Preserve shade trees. * Agroclimatic risk management. * Production management. * Registry and control. * Protect soil composition (neither overload nor wear).	* Case of Cope Dota. * Case of Cope Tarrazú. * Case of Cope AgroPal. * Platforms of public institutes. *Case of Innobovino.
Hydrological footprint	* Precision irrigation systems. * Reduction of residual biomass discharges into rivers. * Reduction of contamination by agrochemicals in water.	* Substantial reduction of the hydrological footprint. * Agroclimatic risk management. * Introduction of new products in the territories (diversification). * Mitigation of public health problems (chemicals).	* Case of Cope AgroPal. * Intelligent greenhouses. * Case of Cope Dota. * Case of Cope Tarrazú. * Case of Banana.
Agrochemical's toxicity	* Specifically design substrates with AI. * Development of substitute bio-inputs. * Precision application systems.	* Replacement of agrochemicals with bio-inputs. * Reduction of agrochemicals usage. * Productivity improvement. * Public health improvement. * Biodiversity conservation. * Increased circularity of production processes.	* Case of Cope Dota. * Case of Cope Tarrazú. * Case of Cope AgroPal. * Case of Cope Pila Angosta. * Case of Banana.
Integration to ecosystems	* Soil analysis sensors. * Specifically design substrates with AI. * Early warning systems. * Precision irrigation systems. * Precision application systems. * Apps for cattle raising. * Use of residual biomass and reduction of discharges on ecosystems. * Bio-inputs and biodegradable substances.	* Preserve shade trees. * Agroclimatic risk management. * Substantial reduction of the hydrological footprint. * Biodiversity conservation. * Development of regenerative practices.	* Case of Cope Dota. * Case of Cope Tarrazú. * Case of Cope AgroPal. * Platforms of public institutes. * Case of Innobovino.

Source: Own elaboration.

6. Conclusions

After doing a comprehensive study of the agricultural sector in Costa Rica, covering representative cases of more than 95% of the agricultural production and biggest livestock activity. It was possible to find evidence that supports the idea that innovation in the agricultural sector can empower a sustainable transition in rural territories. Just as the theory predicts, agricultural innovations are centered on two trends: bioeconomy and digital technologies. These proved to be capable of making the agricultural systems more sustainable and better adapting to the ecosystems they are embedded into.

In the case of bioeconomy, it was possible to identify three areas of impact: substitution of inputs, circular use of wastes, and integration into local ecosystems. Across all the productions that were studied, there is a trend to substitute agrochemicals and chemical inputs in general with biochemicals, or at least biodegradable substances, lessening their environmental impacts; this specific contribution goes in line with biotechnology. Second, in the cases of coffee and oil palm, there are several active strategies to make better use of the biomass, some directed toward increasing the value of their main product, others relate to the use of the residual biomass; this contribution goes in line with the bio-resources focus. Third, in all the cases, there are initiatives aimed at a better integration of productive systems and ecosystems; these are related to the bio-ecology trend.

For the use of digital technologies, most of the innovations aim to increase the precision and information systems around agricultural production. It was possible to find two main uses for technologies: as administrative support and to increase the precision of application of substances. The use of administrative support tools is general when considering the level of medium and big enterprises; for smaller producers it isn't that clear, as some use them and others not; but it's undeniable that these technologies improve the economic-administrative capabilities and results. On the other hand, there are some precision systems being used to control the application of substances. These have proven to reduce the use of chemicals and water, making a great contribution to the sustainability of agricultural productions.

One major finding of this research is that it seems that the potential of these trends of innovation to foster economic development sustainably is maximized when they are combined. This conclusion comes specifically from the case of Project One in the coffee industry. The project used digital technologies, like sensors and artificial intelligence, to make the most of their residual biomass, and duplicated the productivity of their plants. They developed this project thinking about the future of agriculture in the country, currently they are having dialogues with the Ministry of Science and Technology.

It's necessary to observe that in Table 2 most of the evidence comes from cooperatives. This is not because only cooperatives were studied, but because the cooperatives have an active role in the democratization of innovations in Costa Rica, which is a paramount finding of this research. Collaborative governance forms in the agricultural sector act as mechanisms to enhance the absorptive capacity of innovations by small and medium-sized producers. These forms of governance have a key role in the incorporation of technology into technique. This is because some of these technologies are too expensive or complex for small-medium producers, but not for the collective, which can afford them or collectively hire specialists to use them. In fact, all the collaborative organizations studied have their own department dedicated to innovation and technique improvement.

It's mandatory to put forward several lines of research and concerns that arise from these findings. First, even if the direct sustainability of the sector and the territories where the productions are is improved, it's not possible to establish such a conclusion when considering a global scenario. In the case of the bioeconomy solutions, there are questions around the use of land and the production of biomass, as its uses can compete. In a world ruled by market prices, some basic necessities can be ignored in order to maximize benefits. Also, the high demand for biomass can affect the soil and water quality. The issue with digital technologies is the use of water for cooling servers and the extraction of minerals for its components. In synthesis, the direct improvements of sustainability can have some indirect negative effects; in a worst-case scenario, it can turn out to be an exportation of environmental impacts; this needs to be addressed in future research.

Finally, these innovations have impacts on rural development by several channels, aside from the obvious ones. As was shown, innovations in the agricultural sector enable products of higher value, which allows rural territories to capture a bigger share of incomes. This can connect with other activities in the territories. Second, a transformation in the agricultural sector toward industries that produce more income can make rural territories more attractive to firms, making investments in infrastructure more profitable. This is paramount, as one of the difficulties the digitalization of agriculture faces is the lack of infrastructure, as the concentration of the population makes rural territories less attractive to firms than urban areas. Also, these trends of innovation imply the development of more complex capacities in the rural population. The combination of all these aspects can lead to

a new way of rural development, one that proposes rurality as a strategic alternative to development, not just a name for periphery.

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