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RESEARCH ARTICLE

Barriers and enablers of the use of digital technologies for sustainable agricultural development and food security: Learning from cases in Mali

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Digitization in agriculture is gaining momentum in developing countries. Digital technology aims to improve linkages along the agriculture value chain, thereby enabling farming communities and systems to recover from stresses and to absorb shocks to which farmers are exposed. However, there is the concern that digital technologies have not benefited the agricultural sector in a sustainable way. Stakeholders along the agriculture value chain need significant amounts of information to which they do not have access. In Mali, smartphones and earth observation data are used to support the development of land tenure information services and to improve agriculture statistics. To multiply business opportunities, the scope of the use of these technologies is being expanded to include agronomic advisory next-gen, franchised farm extension services. This article aims to evaluate these initiatives to further understand the way digitization could contribute to sustainable agricultural development and food security. In addition, it aims to determine how effective these technologies are under different conditions and how they can contribute to better sustainable development outcomes. Most evaluation studies of agriculture technology place emphasis on the economic aspects of productivity, profitability, and technical efficiency of the technology and the implications for users' livelihoods. This study considers technology as a socio-technical phenomenon to understand the underlying processes that may enable or constrain the takeoff and the sustainability of technology. Furthermore, understanding these processes provides valuable theoretical and methodological insights to stakeholders for necessary adjustments of technology to given biophysical, socioeconomic, cultural, and cognitive conditions.

Keywords: Innovation processes, Technological change, Agriculture, Food security, Mali

Highlights

- The practical challenges for implementing digitization projects are as important for the development of digital technologies as the potential outcomes of the process.
- The uptake and sustainable use of technology are the outcomes of an iterative process between trials, errors, and redesign including addressing practical challenges of technology deployment at scale.
- The technology diffusion and intake could make a leapfrog in developing countries if a feedback mechanism between design and use is integrated at the onset to the technological change.
- Unlike other technologies such as seeds and fertilizers in which adoption and use are mainly based on individual decisions and performance of farmers, sustainable digitization requires a collective performance between technology beneficiaries and service providers.

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1. Introduction

The use of digital technology in agriculture is gaining momentum including in developing countries. Digitization aims to improve networking and linkages along the agriculture value chain, thereby enabling farming communities and agriculture systems to recover from stresses and to absorb shocks of different origins to which farmers and their environment are exposed. However, there is the concern that digital technologies have not benefited the agriculture sector in a significant way especially in Sub-Saharan Africa (Deichmann et al., 2016; The Technical Center for Agricultural and Rural Cooperation [CTA], 2019). The use of new technology in the field of agriculture and food security has been discussed widely in the literature. Much of the focus of the adoption literature is on individual farmers' attitudes and socioeconomic characteristics and the characteristics of the technology (Baumüller, 2012). The technologies are mostly promoted based on the potential they provide in terms of economic fallout, productivity gain, and market opportunities both for companies and famers (Baumüller, 2012). As a result, much of the published literature on technology adoption in recent years has focused on methodological issues, trying to model the process of technology adoption and to quantify empirical measures of the importance of different factors affecting adoption (Doss, 2006). Other studies of adoption and diffusion focus mainly on descriptive statistics. However, simple descriptive statistics do not offer much insight into the process of technology adoption or productivity growth.

Still other studies have stressed the importance of the context in which the adoption and diffusion of the technology (CIMMYT Economics Program, 1993; Marra et al., 2003) take place. Therefore, it is widely recognized that the potential of technologies may remain unexpressed depending on the social, economic, political, and infrastructural factors that affect the performance of specific technologies and the potential interest of farming communities in new technologies (Vanlauwe et al., 2019). The importance of the interaction among these factors is highlighted by Ojiem et al. (2006) who refer to it as "socio-ecological niche" for technologies and by Nelson and Coe (2014) who describe it as the "option by context." Along the same line, studies have considered the way different categories of power such as gender, land size, and access to information impact the process of technology adoption (Schnurr and Addison, 2017). Other studies put weight to the argument by warning against assumption of scale neutrality and rational adoption while acknowledging the systemic nature of on-farm decision making (Whitfield et al., 2015).

By putting an emphasis on digitization, this article makes the distinction between seed, fertilizer, and pesticide technologies channeled through extension workers, and digital technologies as new tools in the field of agriculture and food security, which are not necessarily distributed through extension workers but through an entire technological infrastructure that goes beyond farmers and extension workers. The new technologies are promoted by different channels, including private companies providing digital services, and national and international research institutions. In such context, the uptake and the use of technologies involve different stakeholders who relate to one another using the promoted technology. In this regard, and in line with current scholarship, the present study approaches technological innovation as a socio-technical phenomenon whereby the interaction between technology and users is not mediated only by end-oriented activities of designers but also by sociocultural and environmental conditions (Berkhout and Glover, 2011; Jansen and Vellema, 2011). These understandings conceive of technology as a more fluid assembly of both social and technical components and of socio-technical change as situated, iterative, and contingent (Jansen and Vellema, 2011; Crane, 2014). Informed by insights of science and technology studies, scholars analyze the processes of adaptation, creolization, hybridization, and incorporation as something moving from the periphery to center stage and technology as something people do, make, or remake, not something they receive or adopt (Glover et al., 2019). Making and remaking of technology also suggests taking into consideration feedback loops and mechanisms (Pawson et al., 2004; Meadows and Wright, 2009) within the socio-technical system. Given the current debates on the social implications of technological innovation such as technological lock-in, whereby technological systems develop along established pathways from which it is difficult and costly to deviate (Clapp and Ruder, 2020), making and remaking of technology becomes increasingly important. Furthermore, the double-edged nature of technology whereby optimism about the potential outcomes coexists with the risks of unintended consequences of technological innovation (Jasanoff, 2016; Clapp and Ruder, 2020) make it of outmost importance to understand these complex processes of technology development.

As such, understanding the underlying processes that may enable or constrain the takeoff and the outreach of technology is critical for future and sustainable intake by local communities. Furthermore, understanding these processes provides valuable insights to the stakeholders of technological innovation, including designers, for necessary adjustments of technology to a given biophysical, socioeconomic, cultural, and cognitive condition.

It is therefore important to investigate the context of technology penetration in Mali where, along with other Sub-Saharan countries, attempts are made through the three selected cases to tap into the potential of digitization for sustainable agricultural development. The article therefore addresses the question: What is it about digitization that may enable or constrain its takeoff for sustainable agricultural development and food security in Mali?

Beyond individual farmer adoption, the article investigates the different contexts in which technologies are used in Mali, the mechanisms that are enacted in these contexts and the sustainability of development outcomes produced by the technology in its context. Section 2 presents the methodological choices used to shed light on nascent digitization in the context of Mali. Section 3 describes the 3 cases that capture the current situation of digitization in the field of agriculture and food security in Mali. Findings are presented in Section 4. The crosscutting issues among the cases are discussed in Section 5 before drawing conclusions on digitization in contexts comparable to those of Mali.

2. Methodological approach

In order to evaluate the effectiveness of digitization, this study has been inspired by the realist evaluation approach (Pawson and Tilley, 1997). Realist evaluation is a theory-driven evaluation that seeks to test and understand underlying program theories. It has an explanatory quest in that the program theories are tested to refine them for better policy and decision making. The realist evaluation goes beyond the simplistic questions of "What works?" or "Does this program work?" to rather deepen the reflection on specific programs or projects function by asking, "What works for whom in what circumstances and in what respects, and how?" (Pawson and Tilley, 1997).

The choice of the realist evaluation stems from the realist stance that research concepts are emergent rather than predictable, especially in the socio-technical system composed of technologies, the users of technologies other than practitioners, and the institutional environment around them. Sayer (2000) defines emergence as situations in which the interaction of different aspects gives rise to new phenomena, which have properties that are irreducible to those of their constituents. In this regard, the central tenet of realist evaluation is that interventions work differently in different contexts—Hence, a technology that achieves "success" in one setting may "fail" (or only partially succeed) in another setting because the mechanisms needed for success are triggered to different degrees in different contexts (Jagosh et al., 2015). The second tenet is that mechanisms in realist evaluation are described as the often-invisible forces, powers, processes, or interactions that lead to (or inhibit) the outcomes. Thus, mechanisms can be found in the choices, reasoning, and decisions that people make as a result of the resources an intervention provides; the interactions between individuals or groups; and the powers and liabilities that things, people, or institutions have as a result of their position in a group or society (Pawson and Tilley, 1997; Wong et al., 2013). Therefore, the understanding of how particular aspects of the context shape the mechanism that leads to outcomes is important.

The realist evaluation is a method-neutral approach that follows the line of inquiry of technography (Richards, 2001). Richards considered technography to be basically an eclectic methodology that provides insight into the socio-technical phenomenon of the use of digital technologies, the stakeholders and infrastructures around them and their interactions. Technography is an integrative and realist methodology that seeks to go beyond internalist explanations in which causal relationships are inferred only from bounded configurations of knowledge, skills, and techniques on the use of digital technologies. With interest in the performance of specific tasks, technography seeks to capture interactions between society, nature, and technology (Jansen and Vellema, 2011). In this study, the task is around the use of digital technologies for sustainable agricultural development and food security in Mali.

The context-dependency of the use of technologies motivated the choice of the case studies of 3 initiatives pioneering the budding digitization in agriculture and food security in Mali. The 3 projects were selected to capture the diversity of ongoing initiatives of commercialization and experimental trials of the use of digitization in agriculture and food security in Mali. The rational for including the projects under experimental trials was to detect at the early stage what is there that could contribute to the debates on digitization in the context of developing countries like Mali.

We adopted an intensive, in-depth study of each project involving the use of new technologies (Gerring, 2004; Yin, 2013). The case studies provide a basis for a cross-case analysis that aims to distil cautious and generic causal inferences about the mechanisms of change triggered by the use of new technologies at different scales and in different contexts (Vellema and Ton, 2013). From field scoping to feedback events with stakeholders, 75 individual interviews and 8 focus group discussions involving 80 stakeholders were conducted on the sites of the 3 projects. In-depth interviews and focus group discussions were conducted with different categories of users of Senekela/Sanji and spurring a transformation for agriculture through remote sensing and imagery for smallholders/activating business entry points and leveraging agriculture (STARS ISABELA) including male, female, young, and elder farmers. The stakeholders involved in Sentinel-2 Agri were targeted with key informant interviews. Respondents were identified through purposive snowball sampling (Biernacki and Waldorf, 1981) whereby the first identified respondent refers to the next eligible one. Fifteen individual farmers who did not use any of the technological services were also interviewed. For technology users as well as for nonusers, the number of respondents was determined by data saturation (Luna-Reyes and Andersen, 2003), which was considered to be reached when no new information was obtained from the interviews. Field observations on project sites were conducted by the researchers for each case. A total of 4 feedback events with 162 participants were organized including one for each initiative and a final one to discuss and cross-check the findings with stakeholders. The participants at the feedback events during which the findings were presented included the users of the technologies, service providers, researchers, extension officers, nongovernmental organizations (NGOs), policy makers, and development agencies involved in the projects. Data analysis followed a "retroductive" approach as required for realist evaluation. Retroduction refers to "the identification of hidden causal forces that lie behind identified patterns or changes in those patterns" (Wong et al., 2017). Retroduction uses both inductive and deductive reasoning and includes researcher insights to understand generative causation, by exploring the underlying social and psychological drivers identified as influencing intervention outcomes (Gilmore et al., 2019). Retroduction was combined with content analysis as a research method for making replicable and valid inferences from data to their context, with the purpose of providing knowledge, new insights, a representation of facts, and a practical guide to action (Krippendorff, 1980). Thematic content analysis (McPeake et al., 2020) was used to select quotations that support thematic

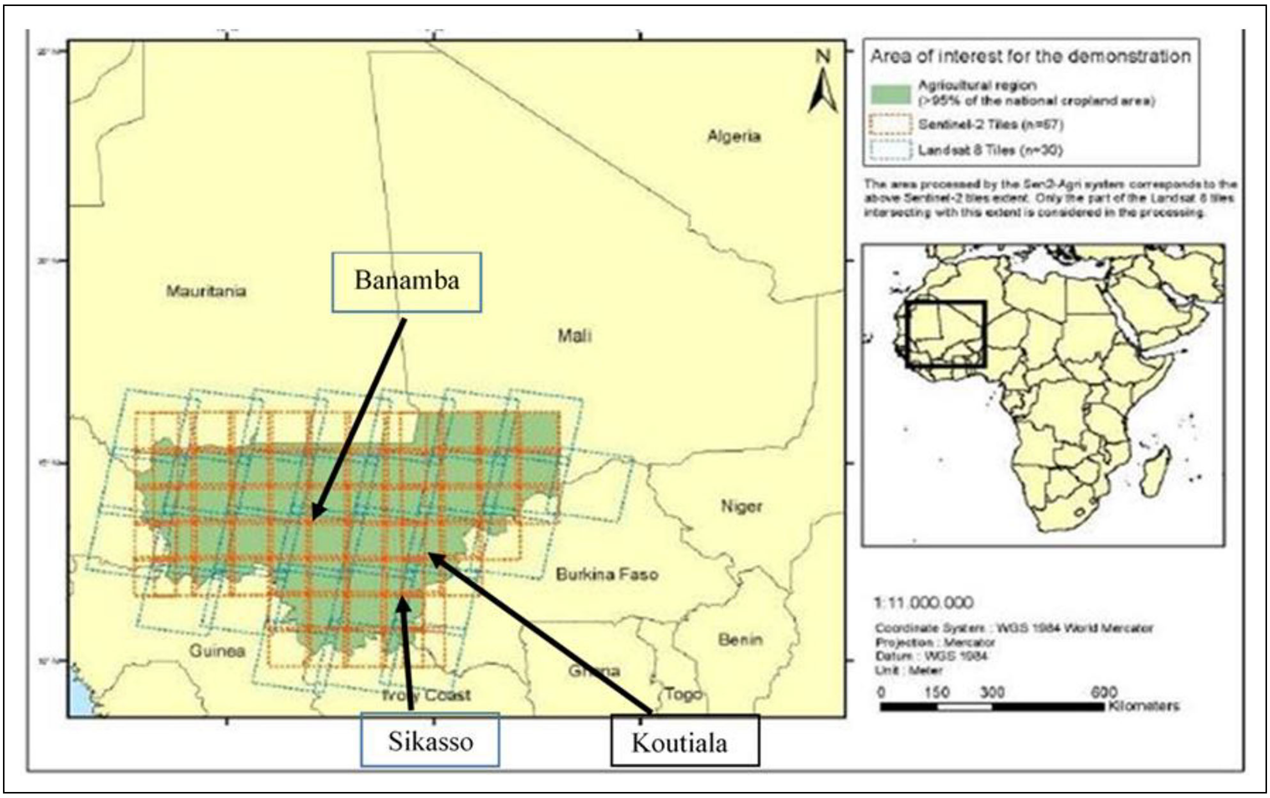

Figure 1. Map showing Sentinel-2 tiles and the 3 study areas. Source: http://www.esa-sen2agri.org/system-demonstration/national-sites/mali/. DOI: https://doi.org/10.1525/elementa.2020.00106.f1

analysis of barriers and enablers to digitization. The 3 projects are described in the next section.

3. Description of the cases and sites

3.1. The service provision through the mobile phone (Senekela/Sanji):

The contribution of Senekela/Sanji to sustainable agricultural development and food security lies in its goal of helping farmers adapt to climate change by providing them with useful technical, market, and weather information for better decision making regarding farm management practices under changing circumstances.

The service provision through mobile phone requires that farmers own a mobile device to make a call or receive SMSs. In Mali, the estimate of the mobile penetration in 2017 was 62% (11.1 million unique subscribers). That penetration rate is projected to reach 66% in 2020 (GSMA, 2017).

Despite the literacy rate of 45% for men and even lower for women above 15 (Institut National de la Statistique du Mali, 2017), there is a high penetration rate of mobile phones in Mali, including in the rural areas. The use of mobile phones for service provision is represented through the twin projects Senekela/Sanji. The two services have been implemented by the mobile service provider Orange Mali. *Senekela* is the translation of the word “farmer” in Bambara, Mali’s most widely spoken language. The project consists of creating a call center to facilitate real-time exchange of information between farmers and a panel of rural development specialists called “agric-advisors” hired by the telephone company. They are tasked to provide, in French and in available local languages, advisory services and guidance to registered farmers in response to all the issues of concern they may have in relation to farming. The services include but are not limited to advice on agriculture practices, market information, and commodity prices. The test phase of the project has been launched in 2013 in the Sikasso region before being extended to the Koulikoro region (**Figure 1**). After the test phase in the 2 regions, the commercial phase started in 2014 and was supposed to cover the entire country. Therefore, the call center has been staffed with more agric-advisors. According to official sources, the service is available from Monday to Friday from 8:30 AM to 4:45 PM and on Saturday from 9:00 AM to 1:00 PM. The call center is reachable through the number 37333. For each call, the client is charged 25 FCFA (about 4 cents US) per minute. The partners of the project include the national agriculture research institute (Institut d’Economie Rurale [IER]). It provides the agric-advisors with updated reference data on the crops at the national level. The NGO Association Malienne pour la Sécurité et la Souveraineté Alimentaires (Afrique Verte) provides the market information and the prices of agriculture commodities. The International Relief and Development (IRD-Blumont), through its project Strengthening Community Initiatives for Resilience to Climate Extremes (RIC4REC), contributes to building agricultural advisors’ capacities on climate change and climate smart agriculture. It provided financial and technical support to include more local languages and to assist the adoption of the technology in its areas of intervention by subsidizing the phone calls.

Senekela goes along with Sanji, which means “rain” in Bambara. Sanji is an SMS service that provides weather forecast information to registered farmers through mobile phones. The mobile service provider Orange Mali gets weather forecast updates from the private company Ignitia that specializes in providing weather forecast information. Registration for the service is a prerequisite for farmers’ access to Sanji weather forecast information. Farmers choose the language (Bambara or French) in which they wish to receive the text message (SMS). It is recommended to farmers to stand in their field when registering the first time. The aim is to allow the geolocalization of their field by the system for them to receive weather forecasts with an accuracy of 2-km radius around the field. To receive the daily SMS, a minimum balance of 25 FCFA (4 cents US) must be available in the phone at 7 AM the morning of the forecast.

Senekela and Sanji have been investigated in Banamba and Sikasso (**Figure 1**), in the 2 regions initially selected for the test phase. The introduction of the technology has been different in the 2 regions. The process has been supported by the project RIC4REC under the IRD in Banamba, and not in Sikasso. The 2 sites present some contextual differences described below.

Banamba is one of the 7 districts (circles) of Koulikoro, the second of the 8 administrative regions of Mali. Agriculture supports more than 80% of the population. Located 150 km in the North of Bamako, Banamba circle falls in the Soudano-Sahelian agroecological zone with the annual rainfall ranging from 500 to 800 mm (Akinseye et al., 2016). The cropping pattern is dominated by millet and sorghum. The recent attempt to reintroduce cotton production in the area failed, resulting in the pullout of the cotton company after 5 years’ experience. The extension services and rural advice are mainly channeled through the national directorate of agriculture with limited geographical coverage and insufficient access to extension services by farmers.

Sikasso is 1 of the 7 circles of the third administrative region of the same name. Located 370 km to the South of Bamako, Sikasso falls in the Soudanian agroecological zone. It receives the annual rainfall ranging between 800 and 1,100 mm (Akinseye et al., 2016). The greenest region of the country, Sikasso is at the heart of the cotton belt. The circle is also one of the breadbaskets of the country. The cropping pattern is composed of cotton, cereal crops, vegetables, and fruits. As such, there is an overlap of extension services provided by the cotton company and the national directorate of agriculture. The geographical coverage by extension services is one of the best with better access to rural advice by farmers.

3.2. STARS ISABELA

STARS is an acronym standing for spurring a transformation for agriculture through remote sensing and ISABELA is an acronym standing for imagery for smallholders/activating business entry points and leveraging agriculture. The project was funded by the Bill & Melinda Gates Foundation and uses mobile (smartphones) earth observation data (mostly from satellite and Unmanned Aerial Vehicles [UAV]) to support the development of land tenure information services in Koutiala. Since the transaction volume for land *strictu senso* in target rural areas remains very limited, there is little business opportunity in the land tenure service, and therefore, they are expanding the scope to include agronomic advisory services (essentially next-gen, franchised farm extension services). According to the field data collection protocol (Blaes et al., 2015), the aim of STARS ISABELA is to delineate field boundaries, discriminate between crop varieties, monitor crop growth conditions and phenological stages, quantify intra-field spatial heterogeneity throughout the growing season, and set up a spectro-temporal and textural signature library. Thus, by accurately delineating field boundaries, STARS service is supposed to contribute to sustainable agricultural development and food security by preventing conflicts among farmers but also by reducing fertilizer use, so that it will not impact the environment and farmers’ expenses.

The project has been implemented on 2 sites including Sougoumba in the constituency of Koningué in the district of Koutiala and at the station of the regional hub of International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) in Samanko (**Figure 2**). Two types of activities were conducted in Sougoumba. The first activity consisted of the soil fertility trial with various treatments conducted in the fields of 50 farmers. The fertility trial was conducted under the 5 major crops grown in the villages—cotton, maize, peanut, millet, and sorghum. These crops characterize the cropping pattern in the district of Koutiala known as the district of “white gold” to refer to the importance of cotton production as the main driver of the agriculture system and food production in the area. The cotton industry that includes gearing and oil processing factories has made Koutiala the second most industrialized city in the country following Bamako. The combined effect of industrialization and the fast-growing population of the city with the national average annual growth rate of the population 3.6% (Traoré et al., 2011) is exacerbating the pressure on natural resources resulting in more conflicts over agricultural lands in the district. Farmers confirm that the conflicts erupt mostly during the rainy season and the long court procedures required to resolve these conflicts is time-consuming and detrimental to agricultural production and food security.

The trial in farmers’ fields was designed not only to create the conditions for joint monitoring by farmers and field technicians but also for farmers’ learning based on their own field observations from the visible outcomes of the fertility treatments. For each crop, 4 fertility treatments were conducted including 1 with zero fertilizer and the 3 others with different amounts of different fertilizers applied during the sowing or at the earing stage. Crop and plant growth variables (chlorophyll content, leaf area index [LAI], soil cover fraction, development stage, soil moisture, and plant height) were measured every 2 weeks in five 2×2 m quadrats within each plot to monitor and characterize crop growth and development conditions. Along with the ground measurements, the UAV imaging data were also collected by field technicians. The

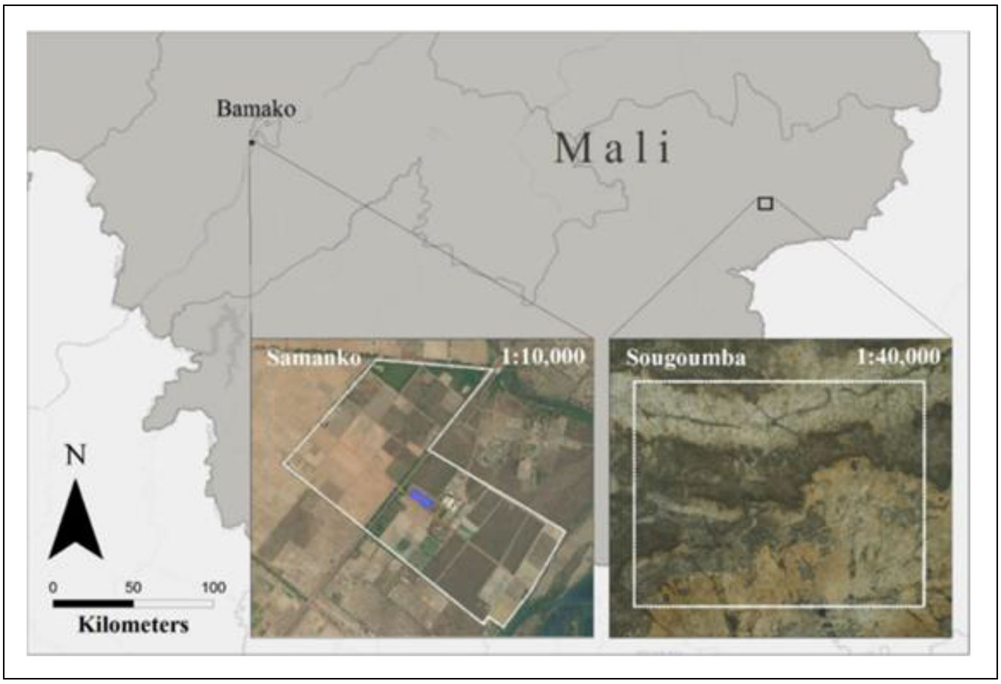

Figure 2. Map showing the site of the project STARS ISABELA. Source: Gooskens (2016). STARS ISABELA = spurring a transformation for agriculture through remote sensing and imagery for smallholders/activating business entry points and leveraging agriculture. DOI: https://doi.org/10.1525/elementa.2020.00106.f2

contrasted responses in canopy development, aboveground biomass, UAV images, and grain yield per treatment were discussed among farmers and field technicians in a feedback event organized for that purpose. The second activity consisted of an intensive field measurement campaign and a biweekly remote sensing imagery acquisition (UAV and very high-resolution imageries). A study area of 10 × 10 km box was defined for that purpose. The images database was supposed to contribute to the development of an information service that could help strategic decision making around land tenure by delineating the boundaries of fields, thus avoiding conflict over resources. The trials were conducted in 2014 and 2015.

A kit of rain gauges and a notebook for record-keeping was provided to the 50 farmers enrolled in the trial. A kit for the postharvest management of groundnut was provided to participants growing that crop.

The ICRISAT station hosted the calibration tests to estimate the LAI and to analyze the correlation between the LAI and the spectral indices determined by the techniques of remote sensing using drones or sent by satellites for groundnut, cotton, maize, millet, and sorghum, the major crops in Soudanian West Africa.

3.3. Improving agriculture statistics and yield estimation using smartphones, tablets, and satellite imagery (Sentinel-2 Agri)

The primary objectives of the Sentinel-2 Agri in Mali included improving the agricultural statistics, estimating crop yield, and preparing the ground for agricultural insurance with accurate yield and production prediction. Factoring in farmers' vulnerability to changing climate, Sentinel-2 Agri is supposed to contribute to sustainable agricultural development and food security by creating conditions for better assessment of farmers' assets and eligibility for such innovation as agricultural insurance. Sentinel-2 Agri also referred to as Sen-2 Agri combines the use of smartphones, tablets, and satellite images to improve agriculture statistics and yield estimation. Sentinel-2 Agri ensued from the achievements of STARS as shown in the time line below (**Figure 3**):

Valuing the experience, partnerships, and legacy of the project STARS, ICRISAT, and its partners have secured the selection of Mali as one of three Sentinel-2 Agri national pilots in the world, along with Ukraine and South Africa.

In Mali, Sentinel-2 Agri is therefore jointly hosted by ICRISAT and by the national agriculture research institute, IER. Sentinel-2 Agri is intended to monitor crops' growth state at the national level in real time with the accuracy of 10-m resolution. Funded by the European Space Agency, Sentinel-2 Agri aims to provide validated algorithms and good practices for agricultural monitoring by remote sensing. The project focus is on the development of demand-driven earth observation products, calibration, and validation of appropriate algorithms. It relies on the capabilities of the Sentinel-2 satellite's mission, which is a transformative multispectral imager offering globally free of charge imageries with resolution of 10 m with a return time of 5 days.

Typically covering 500,000 km^2 and representing a gross imaging volume of about 4 terabytes (4 Tb) per season, each national pilot aims at demonstrating the scaling potential and robustness of the methods. It thus requires the involvement of the institutions and national

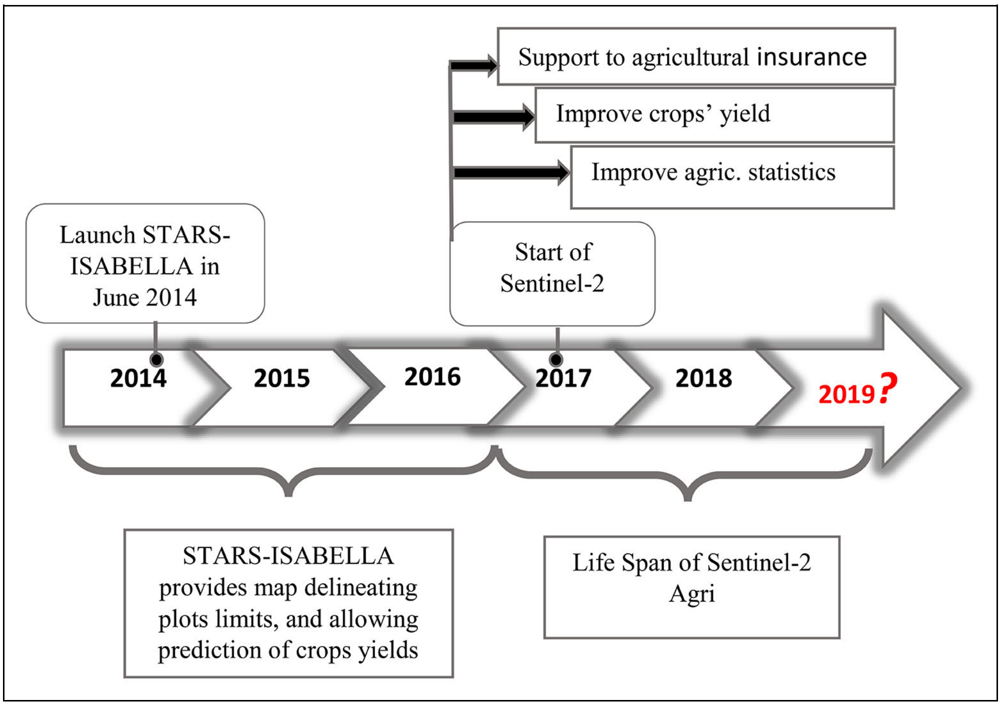

Figure 3. Time line STARS ISABELLA and Sentinel-2 Agri. STARS ISABELA = spurring a transformation for agriculture through remote sensing and imagery for smallholders/activating business entry points and leveraging agriculture. DOI: https://doi.org/10.1525/elementa.2020.00106.f3

authorities, namely the Cellule de planification et de Statistiques (CPS) under the ministry of agriculture, which is responsible for agricultural statistics and for monitoring the agriculture production season in Mali. CPS is meant to provide national statistics to IER for calibration of compiled data generated through the Sentinel-2 system.

The description shows that Senekela/Sanji is the only technology package in which farmers are involved with the commercial use of services. STARS and Sentinal-2 are experimental and mostly conducted at a high level by researchers and civil servants responsible for the collection of agricultural statistics data.

4. Findings

The focus of the findings is on the features of the technologies involved in the 3 projects, the socioeconomic conditions in which the technologies are used, the perceptions of and the reactions of users to the technologies, as well as the barriers to usability and sustainability of the technologies and the context–mechanism–outcome configuration.

4.1. The features of the technologies involved in the 3 projects are summarized in Table 1

4.2. The socioeconomic conditions of the use of the new technologies

4.2.1. Senekela/Sanji

In Banamba and Sikasso, the penetration rate for mobile phones is even higher than the national average. In Banamba, 87% of interviewed farmers in 4 villages own a mobile phone. In Sikasso, 92% of interviewed farmers in the 5 villages covered by the study own a mobile phone.

4.2.2. STARS

All the 50 participant farmers who provided plots for STARS fertility trials were men. Although women play an important role in farming activities, men are responsible for land allocation decisions in Mali. Seventy percent of them are above 40 years old and heads of their production units and therefore involved in the decision making on farming. French is the official language of Mali and the major medium of communication with the technologies; however, 79% of the 50 farmers don't speak French, though some can read Bambara. Our data show that 85% of the decisions in relation to the type of crops to grow and 88% of the decisions on the amount of fertilizer to apply are made by the heads of production units.

4.2.2.1. Sentinel-2 Agri

Sentinel-2 Agri is mostly based on the analysis of data transmitted by the satellite bearing its name. On the ground at the station, conditions include the availability of electricity as well as a high-speed internet connection and high-capacity server. It is specific in that farmers are not involved in the process. The project is more implemented at the national level. It involves IER supported by ICRISAT through the provision of funds for the access to high-speed internet. The role of IER consists of analyzing the satellite-generated data on the crops and fields. These data are cross-checked with the field data collected by sentinel enumerators. The synthesized data are calibrated against the official data collected in the area by the enumerators under the CPS Enquêtes Agricoles de Conjoncture (EAC). The EAC is organized annually under the auspices of the Ministry of Agriculture.

Table 1. Technological package of the 3 projects. DOI: https://doi.org/10.1525/elementa.2020.00106.t1

Project	Equipment Involved	The Funding Partners	Target Audience	Purpose of Technology
Service provision through mobile phone	Mobile phone	Orange Mali, RIC4REC	Farmers	Improve farmers decision making by reducing uncertainty through provision of advisory services, technical guidance, and weather forecast information
STARS ISABELLA	Satellite, on ground GPS, camera, manual on-screen digitizing smart tablet, unmanned aerial vehicles	Bill & Melinda Gates Foundation ICRISAT	Farmers and research institutions	Develop land tenure information system, delineate field boundaries, and anticipate conflicts that erupt during the rainy season. The long court procedures required to resolve these conflicts is time-consuming and detrimental to agricultural production and food security
Sentinel-2 Agri	All equipment involved in STARS along with high-capacity server, a reliable access to internet and reliable availability of electricity power	European Space Agency	National agriculture statistics and planning offices and research institutions	Improve agriculture statistics and yield estimation to prepare the ground for agricultural insurance with accurate yield and production prediction

STARS ISABELA = spurring a transformation for agriculture through remote sensing and imagery for smallholders/activating business entry points and leveraging agriculture; RIC4REC = Strengthening Community Initiatives for Resilience to Climate Extremes; ICRISAT = International Crop Research Institute for the Semi-Arid Tropics.

Against these socioeconomic conditions, the following section describes the processes at play in the study areas for the service provision using the technologies.

4.3. Perceptions of and reactions of stakeholders to the interventions

In line with the retroductive approach characteristic to realist evaluation (Gilmore et al., 2019), the following quotes are purposefully selected with the aim of exploring the underlying social and psychological generative causation that may explain the intervention outcomes.

4.3.1. Senekela/Sanji

First and foremost, farmers have positive perceptions about Senekela and Sanji as the following quotes from farmers in the village of Ziebougou in Sikasso indicate:

> *We would really wish to know more about these services. Last year for example in our area we faced a big challenge with the Army worms on our maize fields. We treated not to avail; we could have resorted to Senekela if we were familiar with it. (Interview, July 2018)*

In Banamba where farmers use the services, they are found to be useful. In Kolodianla, this famer who is a subscriber to the service says:

> *One day I planned to hire labor forces to harvest my field, a soon as I got the SMS that it is going to rain, I decided to reconsider my decision as they cannot work when it's raining. (Interview, July 2018)*

A group of ladies tell the following story about the usefulness for decision making, of the Senekela/Sanji services in Dialako:

> *Last year we wanted to sow groundnut in August, we called the service Senekela to ask whether it is advisable to sow groundnut at this period. The agro advisors advised us not to because it is late, he said. We did not listen, we sow our groundnut in mix-cropping with sorghum, and we harvested nothing. (Interview, July 2018)*

Despite these positive feedbacks, grievances are also expressed in the process. In Sikasso where the services are known but not used, one farmer says:

> *Orange Mali the service provider should reconsider its approach to farmers. I remember, they called me once during the last rainy season to ask about these services. The call was coming from nowhere and I was very busy in my field, it took couple of minutes and it was wasting my time, I decided to cut it off and to continue with my work.*

Although from one farmer, the quote reflects the view of most interviewed farmers in that area where the introduction of the technology was not supported by any other project as substantiates in the following quote from a group of women in the village of Zienbougou:

> *Rather than using phone calls, we prefer people to come to us for direct talks and sensitization. Villagers are usually wary of phone calls coming from unknown callers. (Interview, July 2018)*

In Banamba, where the services are supported by RIC4REC the focus group discussion with farmers revealed that RIC4REC subsidized the access to the service from 2015 to 2017 for the 10 members of each platform created in the 4 villages it covers. The support consisted of providing a subsidy of 3,000 FCFA (around US$6) for the 3 months of the rainy season to the platform. The members of the platform organized themselves to arrange collective calls on a weekly basis (every Friday from 10 to 11 AM). RIC4REC also subsided the SMS service for 45 days with 1,125 FCFA (around US$2.5) for 15 members of the platform. Without subsidy, they find the 25 FCFA/US$0.03/minute of call and per SMS expensive. This is evidenced by the number of subscribers that dropped off at the end of the subsidy. In the village of Dialakoro, the 10 members of the platform unsubscribed from the service. In the village of Fanalé, only 2 members of the platform were still subscribed. This is also substantiated by the fact that in Sikasso where the use of Senekela and Sanji have not been supported by any other measure, farmers claim to have heard about the services but do not use them.

Along with the fact that the weather forecast SMSs are found expensive, the timing namely requirement of a balance at 7 AM to receive the daily SMS is not popular with farmers. According to farmers, it is not easy to have a balance all the time as substantiated in the following statement:

> We usually purchase the phone credit for our urgent needs for communication. In our conditions, it is difficult to secure all the time a minimum level of top-up. The difficult access to the top-up makes the situation worse. *He continues,* in our villages it is often the case that only one person sells the top-up; their limited financial capacity makes the access to the top-up patchy even if one can afford*. Along with these issues with the top-up, key for service provision through the mobile phone is also the billing of the services. In the villages, farmers suspect they are being double charged for the same SMS received, for example.*

The invitations for interviews of the staff from the mobile phone company have been consistently turned down. According to the 2 representatives of the telephone company who participated in the feedback event after the fieldwork, the desire to protect data against misuse by other competitors in a highly competitive sector of mobile

Figure 4. Certificate of participation to the fertility test under STARS ISABELLA (Fieldwork, 2018). STARS ISABELA = spurring a transformation for agriculture through remote sensing and imagery for smallholders/activating business entry points and leveraging agriculture. DOI: https://doi.org/10.1525/elementa.2020.00106.f4

service provision in Mali explains the reluctance to open up the company to outsiders.

4.3.2. Stars Isabela

The fertility tests and the field observations were conducted as explained in the description section. The key outputs of STARS include the results of the fertility tests and yield estimations from the quadrats. The maps delineating field boundaries resulting from remote sensing have been also discussed. A certificate (**Figure 4**) for participation has been handed to farmers after the 2014 results have been shared with them. The next section presents farmers' perceptions and the way they relate to these products.

The certificate of participation as shown below is well appreciated by participants. It encloses the responses of their crops to the tested amount of fertilizer. They believe it is the material testimony of the fertility tests conducted by STARS in the village. Farmers consider the certificate as a diploma, and they will be happy to keep for their personal record to support the learning they received by hosting the fertility trials as reflected in the following quote:

> *Through the fertility trial, I learned that applying more amount of fertilizer than the recommended is not a guarantee for obtaining more yield. The best yield in my case was obtained with the treatment with lower amount of fertilizer. (Interview, June 2018)*

One other farmer adds:

> *I am now convinced that every plot requires a specific management practice. I followed the same practice on the same crop as my neighbor, but I got*

Figure 5. Certificate of occupancy showing field limits (Fieldwork, 2018). DOI: https://doi.org/10.1525/elementa.2020.00106.f5

less yield. The sloppy position of my plot was to blame. (Interview, October 2018)

The certificate of occupancy (**Figure 5**) that STARS was supposed to provide as bedrock for establishing a cadastral plan for the fields has never been issued. Overall, more than 60% of farmers believe that the certificate could give a precise size of their field while showing the boundaries, which according to them will contribute to mediation of conflicts between neighbors over the fields' borders. They think it will also help them better estimate the inputs to apply. However, farmers are divided around the implications the certificate may have. While 68% of farmers believe in the official statement that the certificate is just to testify to the occupancy of the land, 32% are skeptical and suspect that it will lead to other people claiming ownership even if the land is borrowed. The skepticism stems from an unsuccessful government attempt to implement a land identification policy that was supposed to encourage long-term investment on lands. It was objected to by customary landlords who borrowed land to allow other famers to settle.

These suspicions are reinforced by the fact that the STARS process of delivering certificates of occupancy stopped after glitches were observed during the feedback event of the first maps delineating fields. The glitches related to overlapping fields with ill-defined limits, to maps with some fields attributed to the wrong owners or some fields completely missing.

Whereas farmers remain divided on the implications of some outputs, there is an agreement that they were not in fact involved in the process after providing the plots for the trial. According to them, after the identification, the field technicians conducted all the technical parts. Most farmers confirm by saying:

Sometimes you just meet field technicians in the plot. They even don't say hello before getting there. If you want to follow the process, they will advise you to go and continue your work, they will share the results with you.

4.3.3. Sentinel-2 Agri

Sentinel-2 operated in these conditions in 2015. The 4 products of Sen2-agri include a composite of monthly surface reflectance, cultivated land range, maps of different crop types, and vegetation index as well the LAI, in the mid-season. These products are provided every 5 days on the return of the satellite under clear sky conditions. The results and the discussion show that the system is relevant, reliable, less time-consuming than the *EAC*, and the data are more accurate. However, our discussion with the stakeholders involved in the system revealed the issues below.

According to the focal point of the project at IER *in 2017 when ICRISAT pulled out its support, the data could not be analyzed. The internet connection at IER was no longer reliable for the treatment of the data.*

Along with the technical aspect related with high-speed internet as one of the major conditions for the success of these technologies, the collaboration among stakeholders is also pointed out. For instance, the data from the CPS used for the calibration of the data synthesized by IER are reported to be inaccessible. According to the focal point, "excuses are all the time found to unnecessarily delay and ultimately deny the access to data. Which does not help the process to go ahead." Our invitation to the CPS to share findings on Sentinel-2 was also met with no response. No representative showed up despite the promises to send one.

5. Discussion

This section emphasizes the learnings cutting across the different initiatives despite the different areas of application. The introduction of new technologies in agriculture and food security is based on the underlying theory that their uptake and use improve decision making and practices for sustainable agricultural development by helping stakeholders to access knowledge and information and to face current and future challenges while improving business opportunities (Bochtis, 2013; CTA, 2019; Pesce et al., 2019). According to this theory, the uptake and use of the technology are assumed to ensue from the potential outcomes in terms of knowledge, information sharing, improved decision making, practices, and business opportunities. This study shows that the potential outcomes are not a guarantee for sustainable digitization in the field of agriculture and food security. The potential outcomes of the technologies are substantiated by the following facts: Senekela/Sanji as well as STARS contributed to farmer decision making in the areas in which they were active. Sentinel-2 Agri under experimentation has not affected decision making yet, but the time needed for data collection using the technology is recognized by stakeholders during the feedback events, compared to the traditional time and resources needed for data collection through EAC enumerators. However, while the potential of digital technology to inform stakeholders' decisions and practices and to improve sustainable development of agricultural areas is recognized across scale in the different initiatives, it remains untapped because of practical glitches associated with the implementation of the technological packages. The practical challenges of implementing digitization projects such as developing an enabling environment, struggles with communication among users and designers, and the ensuing lack of participation on the part of the intended beneficiaries need to be attended to. The following section will explore these challenges.

The enabling environment such as the cost of the SMS, the timing of the billing, the support by RIC4REC, and the network coverage for Senekela/Sanji proved to be some barriers that restrained the number of users of proposed technologies. This is in congruence with Gallardo and Sauer (2018) who also highlighted the suitability of local conditions as an important factor for the adoption of labor-saving technologies. This also explains farmers' preference for voice mail in relation to Sanji, instead of the text messages in French through SMS, in the context of national literacy rates of 45%. It also shows that the mobile technology was useful to farmers—they wanted to use and access it. However, they were not involved in discussions around how to provide and pay for the technology going forward. Therefore, user participation in technology rollout, pricing, and access needs to be taken into consideration. In addition, the constraining environment as exemplified by the unreliable network coverage and the difficult access to phone credit in certain villages for Senekela, and the prohibitive cost of high-speed internet access that caused the pullout of ICRISAT support to Sentinel-2 in the second year, substantiate the view that the cost of technology and profitability (Turland and Slade, 2020) for the system in which it is introduced is an important driver for its adoption and sustainability.

The miscommunication of field technicians and farmers' feeling of exclusion during the fertility tests associated with STARS ISABELA proved to be sources of suspicion for a number of users. The deterrence these barriers trigger on the part of beneficiaries needs to be dispelled for sustainable uptake and usability of the technologies. In addition, the limited information and resource flows among stakeholders, and the unreliable sources of power for Sentinel-2 Agri constituted additional barriers that underline the importance of accompanying conditions and complementary technologies (Pierpaoli et al., 2013) necessary for the uptake of a new technology.

The suspicion and deterrence on the one side and the misappropriation and misinterpretation of the outputs (maps with inaccurate field limits under STARS) proved mutually reinforcing. The suspicion and deterrence are also visible in the CPS reluctance for data sharing to support calibration under Sentinel-2 Agri. Furthermore, the suspicion and deterrence also reflect the gaps between the intentions of the designers and implementers of technologies and the needs and desires of users. For example, participants in the Sentinel-2 feedback event hypothesized that one of the reasons for CPS' reluctance to allow the access to national data for the calibration of the synthesized satellite data is the recognition that the Sentinel-2 could threaten the EAC, which is not only time-consuming but involves great financial stakes for those involved in the implementation. EAC is an annual survey conducted under the Ministry of Agriculture to provide statistics on agriculture production at a national level. Although the hypothesis is difficult to test, it indicates that hidden mechanisms concealed in vested interests could impede the takeoff of technologies despite the potential benefit for sustainable development of agriculture. The hidden mechanisms are also confirmed by the denial of the access to data from the mobile phone company. The invitations for interviews of the staff from the company have been consistently turned down for reasons that became apparent only during the feedback meeting with stakeholders.

These hidden mechanisms, interests, and agendas are certainly evidence of the complexity of technology adoption, which cannot be explained only by the potential of the technology to achieve desired outcomes or by individual attributes such as farmers' ability to pay, vulnerability and risk, or willingness to use the technology (Yengoh et al., 2009). This study suggests that one must consider the system's ability or inability to establish a feedback loop or mechanism (Pawson et al., 2004; Meadows and Wright, 2009) that allows open-ended discussions between technology designers, implementers, and users to detect the hidden processes that may impede or enable takeoff and sustainable use of technology in agriculture and food security in developing countries. The need for this feedback mechanism is also substantiated by the lack of communication among the stakeholders of the different projects manifest in the perceptions of technology users. We therefore contend that the feedback loop could speed up technology diffusion and adaptation by taking seriously the agency of technology practitioners (Glover et al., 2019). The iterative process of trial and error in which stakeholders work toward matching designers' intention with the need and desire of users is key for technology uptake and sustainable use. This is in line with Rogers (2003) who notes that innovations are more likely to be adopted if they are less complex, lend themselves to trialing, and when results are observable to others (Rogers, 2003; Feder and Umali, 1993). Furthermore, despite the potential outcomes of a technology, shortcomings are identified by stakeholders within all the technological initiatives.

These contextual elements highlight "the need to pay more attention to the material substratum which underpins the very possibility of different courses of action in relation to artifact and which frames the practices through which technologies come to be involved in the weave of ordinary conduct" (Pfaffenberger, 1992). For example, the support by RIC4REC for the use of Senekela/Sanji in Banamba combined with the insufficient geographical coverage by extension services, compared to Sikasso, may explain why Senekela/Sanji is better known and used in

Banamba despite the concurrent commercialization in the two regions.

Taking all these factors into consideration, the article calls for a more iterative, participatory approach to technology co-development, which is likely to prevent not only technological lock-in (Clapp and Ruder, 2020) by opening up stakeholders and technology to some level of flexibility in the process of technology development and adoption but also to speak to the double-edged nature of technological innovation that creates opportunities for opposing perspectives regarding the potential impact of recently introduced technologies (Jasanoff, 2016; Clapp and Ruder, 2020). We argue that the taken-for-granted attitude of technological service providers explains that missing link of feedback mechanism, which delays the takeoff and sustainable use of new technologies in the context of developing countries.

In this regard, to accelerate the uptake and conditions for sustainable use of new technologies in the context of developing countries, it is essential to establish that important axis that might point out the grievances from stakeholders for improvement toward the technology that is appropriate to user conditions.

On the other side, the technology is not 100% accurate, and mischaracterizations by beneficiaries could lead to suspicions. The mischaracterization and the subsequent suspicions are evidenced by farmers' reluctance to engage with the maps that were produced during the sharing of the STARS project outputs because of confusing fields' limits and other fields with erroneous owners' names. However, the discontinuity of STARS and Sentinel-2 Agri ignore the potential for sustainable agricultural development present in the opportunity for the shortcomings to be discussed and addressed during an open-ended feedback mechanism among stakeholders. The discontinuation of these programs increases the time needed for designers to get feedback and take corrective measures.

The literature on the adoption of technologies is mainly focused on the factors that influence individual farmers' ability or decisions to adopt new technology and the profitability of the technology (Doss, 2006; Yengoh et al., 2009). This conveys the impression that technology adoption for sustainability is only an individual endeavor. The adoption of technology is barely analyzed as collective performance (Sidibe, 2013) with a system perspective. From that perspective, technology and its adaptation to specific contexts are the outcomes of trial, error, and complex sociotechnical reconfiguration calling for an agent practice- and process-oriented approach of technological change in a system where different components and stakeholders have complementary roles to play (Glover et al., 2019). On top of that, technology is not always intended only for individual farmers, but for wider system uses, such as STARS aiming to support the development of land tenure information services to prevent conflicts over resources while creating conditions for sustainable investments and Sentienl-2 Agri aiming at improving agricultural statistics and yield prediction. In cases where the technology is intended for individual farmers, the involvement of service providers such as the telephone company and its established platform of agric-advisors makes the technology development a ground for collective performance. Therefore, keeping technological performance high requires mechanisms for feedback on necessary improvements, while maintaining an ongoing effort to match technologies with the conditions, needs, and desires of users. Failing to create such a mechanism is likely to cause the system to break (STARS and Sentinel-2) or to operate below expectation as illustrated by the case of Senekela/Sanji.

6. Conclusion

The findings show that the success of digitization projects is highly dependent on practical challenges for implementing the project and for conciliating the needs and interests of stakeholders. Digitization is therefore a collective performance built on an iterative and interactive process revolving around a feedback mechanism between trial, error, and redesign. The technology diffusion and intake could make great gains if a feedback mechanism between the design and the use is clearly established from the onset and integrated into the diffusion and adoption process. Integrating an open-ended discussion of the way users react to the technologies from the onset of the different projects should have prompted adjustments that may have oriented the mechanisms toward more uptake, usability, and sustainability. It is essential to consider that the technology is designed with embodied intentions that need to be openly discussed and to accommodate the needs, aspirations, and desires of the users driven by specific socioeconomic conditions different from those of the designers and in which the technology is introduced. That suggests that the adaptation of technology to users' conditions and aspirations is essential for technological change and expected sustainability of agricultural development and food security. In this regard, for digitization to contribute to sustainable agricultural development and food security in the context of a developing country like Mali, it is important to consider technology introduction as an iterative and continual process rather than an on-off process. This study also invites us to make a distinction between the adoption of, on one side, digital technologies whereby the users remain engaged in a collective performance with the service provider, and other technologies such as seeds and fertilizers that, once acquired, are used based on the individual decisions of farmers. The study invites thinking of interactive technologies as a collective performance involving an iterative process between stakeholders until the right balance that conciliates the different interests is reached to create the conditions for sustainable outcomes. The transition to a sustainable agricultural system adapted to novel climatic conditions will require this type of approach.

Data accessibility statement

All data relevant to the study are included in the article, further data related to searches and screening will be available from the submitting author on request.

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