The diffusion and adoption of crop disease management practices among banana farmers in Rwanda: The importance of proximity dimensions

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This work is dedicated to the family
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Summary

Although the adoption of agricultural innovations is the foundation of future agricultural development, it has been reported that this is not as effective as it needs to be. The existing literature on the adoption of innovation in agriculture explores different factors that influence this decision. These factors range from personal, social, cultural, and economic to the characteristics of the innovation itself. This research is intended to contribute to the literature by evaluating alternatives to reach banana farmers and to provide advice that promotes agricultural production in the smallholder farming context of Rwanda. Specifically, the research responds to the following: (i) What are the main variables that distinguish banana growers into different farm types in Rwanda, and how do these influence farmers' decision-making processes in adopting new practices? (ii) What role do proximity dimensions play in the knowledge diffusion within formal and informal farmer advisory networks?

Section I of this thesis contains relevant background information, and section II contains an overview of methods used to respond to research questions. Banana Xanthomonas wilt (BXW), an infectious and fast-spreading banana disease, was used as a case to assess how farmers interact with their fellow farmers and with government extension agents to get advice on disease management. Two rounds of interviews were performed using structured questionnaires to collect data. The first interview comprised 690 banana growers from eight representative districts across eight (out of 10) major agroecological zones and provided information to characterize banana farmers across the country. The second interview comprised all banana growers (n = 491) in four chosen villages and provided social network information about BXW management.

Section III of this dissertation is focused on the research question concerning the main variables that distinguish banana growers into different farm types in Rwanda and how these influence farmers' decision-making processes in adopting new practices. Using an exploratory principal component analysis (PCA) of household information collected through a structured questionnaire (n = 690), this research identified 12 variables that are mainly responsible for classifying banana growers in Rwanda. These variables are related to household socioeconomic settings, the banana production system, or access to extension services. Using hierarchical cluster analysis (HCA), three types of banana growers were identified: (i) Beer-banana farmers, who specialize in producing "beer bananas"; (ii) livestock-based farmers, who combine banana production with livestock rearing; and (iii) cooking-banana farmers, who specialize in the production of "cooking bananas." Farmer typologies were distinct and appeared to have diverging behavior regarding the adoption of studied innovation practices. In chapter 3, the use of cell phones was investigated, and in chapter 4, the diffusion of BXW practices was studied. The most important conclusions were that cooking-banana farmers are more likely to have and use mobile phones than other categories, whereas beer-banana farmers have a higher likelihood of not having a phone. Cooking-banana farmers adopted the SDSR whereas beer-banana farmers use the CMU as a BXW control practice.

In section IV, the formal and informal knowledge networks in four villages in Rwanda were investigated. Here, the following research question is investigated: What role do proximity dimensions play in knowledge diffusion within formal and informal farmer advisory networks? This question was answered through social network analysis and statistical network modelling, based on a questionnaire among banana farmers undertaken in four villages. In chapter 5, Boschma's (2005) proximity framework was adapted for use within an agricultural knowledge and innovation system (AKIS) context, based on a literature review. This framework was then tested through an exponential random graph model (ERGM).

Results revealed that the geographical distance (geographical proximity) does not matter until a certain threshold is reached and cognitive and social forms of proximity take over when geographical distance is not important. The ERGM results indicate that farmers are socially close in smaller communities where distance does not matter. There is no significant indication that the geographical location of a farmer does affect the probability of visitation by an official government extension agent. Chapter 6 delved deeper into the formal knowledge network. The distance to farmers was translated to accessibility by applying the cost–distance analysis, a GIS-based analysis to define each farmer's accessibility. Results confirmed that the geographical distance does not predict the probability that an extension agent visits a farmer. Rather, significant factors contributing to the probability of an official government extension agent visiting a farmer are the level of BXW incidence and membership in farmers' groups, such as Twigire-Muhinzi, and farmers' cooperatives.

This dissertation's main conclusion is that, to reach banana farmers, it is important to take into account that they are heterogeneous. In this case, the use of typologies to inform the scaling of development activities is a practical way to account for farm diversities and to fit well into the existing social values and practices. This study shows that proximity dimensions are relevant for the interactions and factors to form advice-seeking ties in informal knowledge networks. However, the effect depends largely on whether the community is dispersed or congregated. Furthermore, the proximity study was relevant to unpack more about what is happening in the informal knowledge networks than in the formal AKIS. The proximity concept can be used to strengthen the Twigire-Muhinzi initiative, an important driver to access information from the formal AKIS.

Zusammenfassung

Obwohl die Übernahme landwirtschaftlicher Innovationen die Grundlage der künftigen landwirtschaftlichen Entwicklung ist, deuten viele Studien über die Einführung, Aneignung und erfolgreiche Verwendung von Innovationen in der Landwirtschaft darauf hin, dass dies nicht so effektiv ist, wie es sein müsste. Diese Studien untersuchen verschiedene Faktoren, die diese Entscheidung beeinflussen, darunter persönliche, soziale, kulturelle und wirtschaftliche Faktoren, aber auch die Charakteristika der Innovation selbst. Die vorliegende Untersuchung soll zu dieser Debatte beitragen, indem am Beispiel von Bananenbauern in Ruanda Alternativen bewertet werden, wie die landwirtschaftliche Produktion im kleinbäuerlichen Kontext durch Beratung gefördert warden kann. Insbesondere geht die Arbeit auf die folgenden drei Fragen ein: (i) Was sind die Hauptvariablen, die kleinbäuerliche Bananenproduzenten in verschiedene Betriebstypen unterscheiden, und wie beeinflussen diese die Entscheidungsprozesse der Landwirte bei der Einführung neuer Praktiken? (ii) Welche Rolle spielen Kriterien der räumlichen bzw. geografischen Nähe (Proximity) bei der Wissensverbreitung innerhalb formeller und informeller Beratungsnetzwerke für Landwirte?

Abschnitt I dieser Arbeit enthält relevante Hintergrundinformationen und Abschnitt II gibt einen Überblick über die Methoden, die zur Beantwortung von Forschungsfragen verwendet werden. Die Bananen-Xanthomonas-Welke (BXW), eine ansteckende und sich schnell ausbreitende Bananenkrankheit, wurde als Fallbeispiel herangezogen, um zu beurteilen, wie Landwirte untereinander und mit staatlichen Beratern interagieren, um Ratschläge zum Krankheitsmanagement zu erhalten. Zur Datenerhebung wurden zwei Interviewrunden mit strukturierten Fragebögen durchgeführt. Das erste Interview umfasste 690 Bananenbauern aus acht repräsentativen Distrikten in acht (von 10) großen agrarökologischen Zonen und lieferte Informationen zur Charakterisierung von Bananenbauern im ganzen Land. Das zweite Interview umfasste alle Bananenbauern (n = 491) in vier ausgewählten Dörfern und lieferte Informationen über soziale Netzwerke zum BXW-Management.

Abschnitt III beschäftigt sich mit derFrage nach den Hauptvariablen, die Bananenbauern in Ruanda in verschiedene Betriebstypen unterscheiden, und wie diese die Entscheidungsprozesse der Landwirte bei der Einführung neuer Praktiken beeinflussen. Unter Verwendung einer explorativen Hauptkomponentenanalyse (PCA¬) von Haushaltsinformationen, die durch einen strukturierten Fragebogen (n = 690) gesammelt wurden, identifizierte diese Studie 12 Variablen, die für die Klassifizierung von Bananenbauern in Ruanda verantwortlich sind. Diese Variablen beziehen sich auf die sozioökonomischen Charaktristika der Haushalte, das Bananenproduktionssystem oder den Zugang zu Beratungsdiensten. Mithilfe der hierarchischen Clusteranalyse (HCA) wurden drei Arten von Bananenbauern identifiziert: (i) Bierbananenbauern, die sich auf die Herstellung von Bierbananen spezialisiert haben; (ii) Viehzüchter, die die Bananenproduktion mit Viehzucht kombinieren; und (iii) Kochbananenbauern, die sich auf die Produktion von Kochbananen spezialisiert haben. Die Typologien der Landwirte waren heterogen und schienen ein unterschiedliches Verhalten in Bezug auf die Übernahme untersuchter Innovationspraktiken zu haben. In Kapitel 3 wurde die Nutzung von Mobiltelefonen und in Kapitel 4 die Verbreitung von BXW-Praktiken untersucht. Die wichtigsten Schlussfolgerungen waren, dass Kochbananenbauern eher Mobiltelefone besitzen und benutzen als andere Kategorien von Bauern, während Bierbananenbauern eine höhere Wahrscheinlichkeit haben, kein Telefon zu haben. Kochbananenbauern haben die SDSR übernommen, während Bierbananenbauern die CMU als BXW-Kontrollpraxis verwenden.

In Abschnitt IV wurden die formellen und informellen Wissensnetzwerke in vier Dörfern in Ruanda untersucht. Dabei wurde der Frage nachgegangen, welche Rolle Nähe-Dimensionen bei der Wissensdiffusion innerhalb formeller und informeller Beratungsnetzwerke für Landwirte spielen. Diese Frage wurde durch soziale Netzwerkanalyse und statistische Netzwerkmodellierung beantwortet, basierend auf einem Fragebogen unter Bananenbauern aus vier Dörfern. In Kapitel 5 wurde das Proximity Framework von Boschma (2005) für die Verwendung im Kontext eines landwirtschaftlichen Wissens- und Innovationssystems (AKIS) angepasst. Dieses Framework wurde dann durch ein exponentielles Zufallsgraphenmodell (ERGM) getestet. Die Ergebnisse zeigten, dass die geografische Distanz (bzw. Nähe) keine Rolle spielt, solange ein bestimmter Schwellenwert nicht erreicht ist; in diesem Fall werden kognitive und soziale Formen der Nähe ausschlaggebend. Die ERGM-Ergebnisse zeigen, dass Landwirte in kleineren Gemeinden, in denen Entfernung keine Rolle spielt, sozial eng zusammenstehen. Es gibt keinen signifikanten Hinweis darauf, dass der geografische Standort eines Landwirts die Wahrscheinlichkeit eines Besuchs durch einen offiziellen Berater der Regierung beeinflusst. Kapitel 6 befasste sich eingehender mit dem formalen Wissensnetzwerk. Die Entfernung zu den Landwirten wurde durch Anwendung der Kosten-Entfernungs-Analyse, einer GIS-basierten Analyse zur Definition der Erreichbarkeit jedes Landwirts, in Erreichbarkeit übersetzt. Die Ergebnisse bestätigten, dass die geografische Entfernung nicht über die Wahrscheinlichkeit aussagt, ob ein offizieller Berater der Regierung einen Landwirt aufsucht. Wesentliche Faktoren, die zur Wahrscheinlichkeit eines solchen Beratungsbesuchs beitragen, , sind vielmehr das Ausmaß der BXW-Inzidenz und die Mitgliedschaft in Bauerngruppen wie Twigire-Muhinzi und Bauerngenossenschaften.

Die Hauptschlussfolgerung dieser Dissertation ist, dass es wichtig ist, die Heterogenität der Bananenbauern zu berücksichtigen, um sie mit Beratungsangeboten zu erreichen. In diesem Fall stellt die Verwendung von Typologien zur besseren Skalierung von Entwicklungsaktivitäten einen praktikablen Weg dar, Unterschiede in landwirtschaftlichen Betrieben sowie soziale Werte und Praktiken der Landwirte zu berücksichtigen. Diese Studie zeigt, dass Dimensionen der räumlichen Nähe für die Interaktionen und Faktoren relevant sind, die zur Entstehung von Bindungen zwischen den Ratsuchenden in informellen Wissensnetzwerken beitragen. Die Wirkung hängt jedoch weitgehend davon ab, ob die jeweilige Gemeinschaft räumlich verstreut oder konzentriert ist. Darüber hinaus hat die Untersuchung gezeigt, dass die Analyse der räumlichen Nähe besser zur Erklärung der Entscheidung in informellen Wissensnetzwerken als in im formellen AKIS eignet. Das Proximity-Konzept kann folglich verwendet werden, um die Twigire-Muhinzi-Initiative in ihrer Funktion als Schnittstelle für den Zugang zu Informationen aus dem formellen AKIS zu stärken.

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Abbreviations

AKIS: Agricultural Knowledge and Innovation System(s)

BXW: Banana Xanthomonas Wilt

CMU: Complete Mat Uprooting

DEM: Digital Elevation Map

EEG: Evolutionary Economic Geography

ERGM: Exponential Random Graph Model

FFS: Farmer Field School

FP: Farmer Promoters

HCA: Hierarchical Cluster Analysis

ICTs: Information and Communications Technologies

MINAGRI: Ministry of Agriculture

NGO: Non-Governmental Organization

PCA: Principal Component Analysis

RAB: Rwanda Agriculture and Animal Resources Development Board

SDSR: Single Diseased Stem Removal

SSA: Sub-Saharan Africa

TLU: Tropical Livestock Unit

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Section I: Background information

1. General introduction

1.1 Background

Crop diseases continuously challenge the livelihoods of Africa's smallholder farmers. One example is banana Xanthomonas wilt (BXW)—an aggressive bacterial disease caused by *Xanthomonas campestris*, which is easily transmitted, spreads rapidly, and has no cure after infection (McCampbell et al., 2018; Tripathi et al., 2009). BXW has devastated banana production in East Africa since the early 2000s. By 2015, the value of losses in Rwanda from BXW was estimated at USD 2.95 million, with a 30% decrease in the number of bananas sold and a doubling in the price of the banana bunch (Nkuba et al., 2015). Besides direct costs, other socioeconomic implications associated with BXW include the cost of control and recovery times necessary to regrow banana trees (McCampbell et al., 2018; Sebikari, 2010). Experts in crop disease management assert that available methods to deal with BXW can completely eradicate the disease when properly applied. However, despite efforts by the government of Rwanda and stakeholders to control and prevent BXW, the disease is still occurring or popping up again in the same areas, a sign of failure to adopt proper prevention and control measures (Sebikari, 2010).

In this research, I investigate the knowledge exchange networks of Rwandan banana farmers to understand the diffusion of BXW prevention and control innovation practices. Traditionally, complete mat uprooting (CMU) was the only officially condoned BXW management technique (McCampbell et al., 2018). The CMU consists of uprooting the entire infected banana mat and burying it in the soil. Although CMU is an effective method because it removes a large number of bacteria inoculum, it has been only partially adopted because it is costly, time-consuming, and severely affects the continuity of bunch harvests (Blomme et al., 2021). Furthermore, farmers are not always motivated to remove the whole banana mat when only one pseudostem may be showing disease symptoms (Blomme et al., 2017). Recently, another technique was introduced: single diseased stem removal (SDSR), which consists of cutting, only the stem that shows symptoms of BXW at the soil level (Blomme et al., 2017; Ntamwira et al., 2016). One of the advantages of the SDSR technique over CMU is that farmers do not need to replant (Ntamwira et al., 2016). Although this new method is better in many aspects, so far the method has failed to gain widespread adoption. Thus, the question is how this new management method diffuses through the banana-farming population.

This particular question falls within an important field of research in the agricultural domain. The research of (small) farmers' adoption of innovations has been an important and classic topic for agricultural sustainable production in past decades (Mottaleb, 2018; Tey & Brindal, 2012). Agricultural innovations have long been developed and advanced to increase farm productivity, more so as the demand for the world to feed its rapidly growing population has increased (Long et al., 2015). Substantial agricultural innovations have been developed with the potential to enhance agricultural productivity; however, low uptake remains a challenge to achieving the intended impact, especially in Africa, where smallholder farming prevails (Adenle et al., 2019; Makate, 2019; Shikuku, 2019).

Agricultural extension systems started in the middle of the 19th century with the Irish potato famine between 1845 and 1851 (because of the destruction of Irish potatoes by fungal diseases), during which the government arranged a technical team to teach farmers how to grow alternative crops (Anandajayasekeram, 2008; Jones & Garforth, 1997). A popular subject in extension studies is diffusion and adoption, which builds on the book "Diffusion of innovations," a famous work by Rogers (1962) in which technology adoption is a central theme. However, despite the progress made to improve the agricultural advisory system, the question of why some farmers adopt certain innovations and why others do not is still a concern of scholars (Mottaleb, 2018; Tey & Brindal, 2012). Although more context-specific factors in terms of sociocultural, economic, and agroecological drivers were added as being important (Schut et al., 2014), there was still no significant move from the one-size-fits-all approach of scaling approaches (Birner & Anderson, 2007). The one-size-fits-all approach is the term used to indicate that new technology is scaled mostly linearly from the lab to field trials and the general farming population as if it is addressed to a single context, regardless of environmental and socio-economic differences between regions and between types of farmers (Tödtling & Trippl, 2005).

This thesis investigates the diffusion and adoption of BXW management innovations through two interrelated processes. First, the thesis investigates how existing BXW management processes fit with the existing social values and practices of banana farmers. In the first part of this thesis, a distinction is made between different types of banana farmers to see how each of these types reacts to information on BXW management and to optimize adoption and diffusion strategies. To some extent, the low uptake of agricultural innovations has been associated with the failure to consider smallholder farmers' diversity properly (Coe et al., 2016; Hammond et al., 2017). However, treating every farm household as unique and tailoring individual strategies to each individual farmer is practically unfeasible and expensive. As a middle road between the one-size-fits-all and the individual approaches, the idea of farmer typologies has recently gained ground (Bartkowski et al., 2022a). To reduce some of the inherent complexity of such a wide diversity, researchers have tried to develop certain farmer typologies (Daxini et al., 2019; Hammond et al., 2017; Köbrich et al., 2003). A typology approach, thus, becomes an effective theoretical framework to explore the factors that explain the adoption of new technology. Thus, different authors argue that typology analysis is a useful tool for tailoring future interventions and policies (Hammond et al., 2017), a decisive factor to adopt innovation (Daskalopoulou & Petrou, 2002), a basis for ex-ante interventions (Lopez-Ridaura et al., 2018), and an explanation of farmers' intentions to respond to several scenarios (Daxini et al., 2019; Nainggolan et al., 2013).

In the second part of this thesis, the characteristics of the advice networks between banana farmers and between banana farmers and extension officers take center stage. The successful adoption of agricultural innovation is positively associated with the functionality of the knowledge networks and the effectiveness of knowledge sharing within an innovation system (Gava et al., 2017; Pratiwi & Suzuki, 2017). Within the last decade, the agricultural knowledge and innovation system (AKIS) literature has adopted a network perspective to explain and predict information flows (Danielsen et al., 2020; Hermans et al., 2017b; Spielman et al., 2011). The characteristics of knowledge networks within AKIS have received considerable attention concerning the different factors that advance or hamper the effectiveness of knowledge networks (Gava et al., 2017; Micheels & Nolan, 2016), but so far geographical factors (i.e., proximity) has not yet received substantial consideration in the AKIS literature. This is even more surprising because it is generally acknowledged that proximity is important in agricultural advice. The reason for this is that the agricultural management advice often consists of tacit knowledge, which is delivered better face-to-face, sometimes requiring demonstration (dos SANTOS et al., 2016; Swanson & Rajalahti, 2010).

1.2 Theoretical framework

This section introduces some of the theoretical concepts that form this thesis' backbone. As the overarching theoretical framework, this dissertation uses the concept of the Innovation System and, particularly, the AKIS. The innovation system perspective provides an analytical framework to study technological change as a complex process of actions and interactions among a diverse set of actors engaged in generating, exchanging, and using knowledge (Freeman, 1988; Lundvall, 1992; Edquist, 1997). The innovation system perspective broadens view beyond business actors directly involved in innovation processes to a multitude of actors that can play a role within innovation processes. Klerkx, van Mierlo et al. (2012) traced the development of the AKIS back to the literature on extension and diffusion that has its roots in the previously mentioned work of Rogers (1962). The complexity of agriculture required a reorganization of knowledge transmission and resulted in a progression of agricultural extension from a technology-oriented approach to systems-oriented approaches (Schut et al., 2014).

AKIS consists of three important elements: (i) the actors, (ii) the networks that facilitate the interaction between the actors, and (ii) the institutions (defined here as "the rules of the game'" (North, 1990) that govern the behavior of the actors and their interactions).

1.2.1 The AKIS actors

In general, there are three important types of actors within the AKIS. The first is part of the National Agricultural Research System (NARS). These consist of the traditional triptych of agricultural research, (often at specialized universities), state-sponsored extension services, and agricultural education, all of which are involved in the production and dissemination of formal knowledge. However, over the years, more actors were considered important for a well-functioning AKIS: financial institutions, such as banks and insurers, and nongovernmental organizations (NGOs), such as consumer organizations and environmental and landscape organizations. The organization of the AKIS can differ from country to country and is often a result of the historical development of the agricultural sector in a country. In some (European) countries, the state-sponsored agricultural extension services have been completely privatized, but in other countries, these extension services still play a significant role (Hermans et al., 2015).

Over the years, the role of farmers within the innovation networks changed. For a long time, farmers were considered more or less passive recipients of knowledge, and this only gradually changed with the introduction of the AKIS concept. Since the 2000s, the flow of information was considered multidirectional. The consideration of a farmer in the system shifted from the adopter of technology to the partner in innovation networks.

Currently, a farmer and their political representatives, such as farmer unions and cooperatives, are seen as equal actors in the process of knowledge co-creation and dissemination. However, the diversity of farmers, defined here as possible disparities in connecting due to norms and attributes that individual farmers possess, makes this consideration controversial (Pratiwi & Suzuki, 2017). In this case, a typology approach becomes a practical means to make sense of the complex relationships between various factors that can influence farmers' tie formation (Darnhofer & Walder, 2014). The typology approach, which classifies farmers based on common characteristics, is a practical way to account for farms' diversity and heterogeneity (Daxini et al., 2019; Hammond et al., 2017; Köbrich et al., 2003). For that reason, such a farm typology approach might be a promising way to take farmers' value systems, which are likely to influence their inclination to adopt an innovation, into account. This does not mean that farm types reflect social values. Instead, farmers belonging to the same type are more likely to share similarities concerning social values. Within an individual's cognitive system, social value is the relative importance that a person associates with experiences. Previous studies have shown that an innovation that is less disruptive to the existing social value, particularly in the farming community, is more embraced than otherwise (Curry et al., 2021; Daghfous et al., 1999). The literature distinguishes farmer types (groups of farmers with almost similar socio-economic traits) and farm types (grouping farms depending on similarity in farming contexts), depending on variables used to build typology (Bartkowski et al., 2022b). In this particular thesis, farmers' attributes and farming systems are used for typology development.

This thesis investigates the AKIS in Rwanda, where agricultural knowledge is channeled through a formal government-led extension service and informal farmer-to-farmer knowledge exchange approaches. The formal extension services are coordinated by the Rwanda Agriculture and Animal Resources Development Board (RAB) under the Ministry of Agriculture (MINAGRI) (MacNairn & Davis, 2018). The formal national extension structures and staff extend to the sectoral administration level. On the other hand, the RAB has established a farmer-facilitated extension model, the Twigire-Muhinzi, to deploy staff to the village level (Silvestri et al., 2019). As such, the Rwanda AKIS still relies heavily on top-down governing through state-sponsored extension services, but the organization at the village levels still allows for some feedback mechanisms from farmers.

1.2.2 Vertical vs. horizontal knowledge networks

The second element of the AKIS concept is knowledge networks. This dissertation places a particular emphasis on the distinction between formal and informal knowledge networks. The vertical knowledge network is associated with the classical linear model of knowledge creation and dissemination, where government-sponsored extension services transmit new knowledge from research institutions to farmers (Hermans et al., 2013). This model is generally characterized by a top-down flow of information and assumes that technologies developed by scientists are best for the current understanding of agricultural systems (Black, 2000). This mode of knowledge transmission is often structured according to administrational subdivisions, and it is institutionalized. Although this classical model has provided significant support to improve farm productivity, it has been criticized for not meeting the broader development goal that reflects the various functions of farming systems (Hermans et al., 2013).

Currently, there is increasing recognition of the importance of horizontal supporting knowledge networks, in which knowledge is spread between farmers (Leeuwis, 2013; Šūmane et al., 2018). In this thesis, the term informal knowledge network is used to describe the exchange of information that occurs through farmers' interactions. Official extension agents do not always reach all the farmers, resulting in unequal opportunities to access new knowledge. In this case, the knowledge gap can be filled by relying on informal knowledge networks (Pratiwi & Suzuki, 2017). Leta et al. (2018) showed more than 50% of farmers rely on their fellow farmers to adopt agricultural innovations. Karangwa et al. (2016) showed that 93% of farmers in east and central Africa acquire banana-planting materials locally from their neighbor farmers. The consideration of informal knowledge networks as a part of agricultural knowledge systems would facilitate the demand-driven extension (Minh et al., 2014), strengthen the use of indigenous knowledge (Šūmane et al., 2018), and facilitate the participation of farmers in research activities in the form of data collection (Beza et al., 2018). The strength of the informal knowledge network is positively correlated with the role the farmer plays in knowledge co-creation (Charatsari et al., 2020). In this case, the informal knowledge network can provide a significant contribution to optimizing knowledge transmission because the co-created knowledge is based on the experience built over time and for specific local conditions.

The informal knowledge network concept shows some similarities with social learning theory. The social learning theory states that individual behavior is acquired through observing and imitating others

(Bandura, 1978; Williams, 2017). For example, in the case of BXW management, when farmers have had experience dealing with the disease, other farmers might seek them out for advice. Therefore, the learning process becomes a process of social capital-building over time that occurs between individuals belonging to either the same or different social settings (Storr et al., 2017). In this case, there is a gradual process of developing cognitive (e.g. increasing specialization and common understanding) and social (e.g. increasing embeddedness in the farming community) forms of proximity.

1.2.3 Institutions

Institutions are the last element of the innovation system. Institutions in this thesis are defined as the "rules of the game" (North, 1990). Institutions facilitate interaction between the actors within an AKIS. In general, two types of institutions are considered relevant for the functioning of an AKIS. The first is the formal institution: the laws and regulations that form the formalized rules of the system. A lack of formalized rules may hamper innovation, for instance, when a lack of intellectual property rights takes away incentives from innovators because they cannot protect their ideas. At the same time, too much regulation and red tape can be detrimental to innovative performance and is a complaint from entrepreneurs and scientists alike (Hermans et al., 2015). The informal institutions consist of the unwritten rules that are formed by the norms, values and culture, and they refer to "the way business is done" between the actors and what constitutes good business and farming practices. These institutions affect how actors interact with each other and relate to their (in) ability to change their behavior and operations to enable innovation.

Within the Rwandan context, the most important institutions within this thesis are the institutions that govern the combat and management of BXW. In this regard, it is important to make an institutional distinction between the CMU, which was officially condoned for years, and the newly introduced SDSR. The official extension system at the national level promotes the CMU as a proven method to be disseminated to banana farmers. Research institutions, on the other hand, acknowledge the alternative SDSR. The SDSR has been tested in the eastern Democratic Republic of Congo and has proven its potential in controlling BXW, as the field that had 80% incidence decreased to 2% in 10 months after the SDSR technique was applied (Blomme et al., 2017).

It is important to note that, within this thesis, institutions are considered more or less stable: they provide the specific context conditions in which actors and networks operate. An important element of institutions is that institutions are thought to facilitate the sharing of knowledge. Actors operating within the same institutional and organizational contexts, which share the same formal and informal rules, are believed to exchange information more easily.

1.3 Gaps in the literature

1.3.1 Proximities in AKIS

Although extensive research has been carried out on the adoption of agricultural innovations since at least the 1970s, there is still a lot to unpack concerning farmers' access to information. One of the concepts yet missing is the role of proximity dimensions in AKIS as a factor to reach farmers. Proximity dimensions have been extensively discussed in evolutionary economic geography (EEG), but only a few attempts have been made to evaluate how they could be operationalized in studies of the knowledge networks of AKIS systems (Agrawal et al., 2008; Torre, 2013; Torre et al., 2019b).

In the early 1990s, French regional scientists introduced the proximity concept in the study of regional innovation systems as an element to account for the interconnection of industrial dynamics with spatial dynamics (Bellet et al., 1993; Carrincazeaux et al., 2008; Rallet & Torre, 1995). In this case, *proximity* is referred to as an individual's tendency to form interpersonal relationships with those who are close by. Since then, a massive amount of literature, especially in the field of economic geography, has sprung up showing that being proximate drives the creation of ties for knowledge exchange (Abramo et al., 2020; Agrawal et al., 2008; Gullahorn, 1952; Sykes, 1977), but also how proximity shapes social networks (Stopczynski & Lehmann, 2018), influences network dynamics (Lazzeretti & Capone, 2016), social interaction and attachment (Fay & Maner, 2012), social learning (Boschma, 2005) and knowledge diffusion (Abramo et al., 2020; Agrawal et al., 2008; Maté-Sánchez-Val & Harris, 2018).

One of the most influential and most commonly applied proximity frameworks in economic geography has been the proximity framework of Boschma (2005), who makes a distinction between five different forms of proximity: (i) Geographical proximity, which takes into consideration both geographical and functional distance between actors; (ii) cognitive proximity, which accounts for shared knowledge and references; (iii) social proximity, which accounts for social embeddedness and relates actors by shared personality characteristics and social context; (iv) institutional proximity, which considers the extent to which relations are shared in an institutional setting; and (v) organizational proximity, relating actors by a set of laws and rules as well as routines that facilitate collective action (Boschma, 2005).

It is important to note that proximities can act on innovation processes positively and negatively. This is known as the "proximity paradox" (Boschma & Frenken, 2010; Broekel & Boschma, 2012): too little proximity may hinder innovative performance, but too much proximity may create "tunnel vision" and be problematic as well. In addition, caution is needed in operationalizing proximities into AKIS because research into the co-evolution of different forms of proximities and network structures has shown that different types of proximities may rise to prominence over time (Abbasiharofteh & Broekel, 2020; Balland, 2012; Ter Wal, 2013) and the role of different forms of proximity may change over time.

In this dissertation, I will use the notion of proximity to investigate how these forms of proximity shape the vertical and horizontal networks within an AKIS. These five forms can all, or partly, play a role in the formation of knowledge ties depending on the specific context of the AKIS. Based on the review of different proximity concepts as discussed in EEG literature, I will propose a way to operationalize them within an AKIS context. I conducted an empirical investigation using primary data of both spatial factors and relational attributes to assess how geographical, cognitive, and social proximity affect advice-seeking tie formation in BXW management.

Thus, I will introduce some elements of EEG in the study of AKIS. However, I will also argue that the addition of proximity within an AKIS framework is also of interest, not only for AKIS studies but also for EEG, because two important elements of AKIS studies have not received a lot of attention in EEG literature. First, unlike other industrial innovation systems, AKIS is bound to certain geographical characteristics such as climate zones or soil conditions, and, simultaneously, this also has important implications for the distribution of knowledge because the practical knowledge of such production systems is often also highly localized (Mwongera et al., 2017; Verdoodt & Van Ranst, 2003). Second, AKIS literature often embraces lower economic class individuals, especially in Sub-Saharan Africa. However, much of the EEG literature deals with western industrial clusters or well-established agricultural clusters in western countries (e.g. clusters in Ayrapetyan & Hermans (2020) and in Abbasiharofteh & Dyba (2018)).

1.3.2 Integration of formal and informal knowledge networks

The second research gap concerns a mechanism to integrate the informal and formal knowledge network to optimize knowledge transmission. Šūmane et al. (2018) appealed for integrating informal knowledge sharing with the government's formal extension system to boost resilient and sustainable agriculture. Substantial literature shows the relevance of local knowledge in agricultural innovation systems and the importance of placing the farmer at the center of the system. However, little is known about how structural properties of the informal knowledge network and the position of a farmer in a broader knowledge network could be used as entry points for integrating the informal knowledge network into the existing official advisory system. To bridge this gap, a social network analysis was applied to social network information about the management of BXW, from all banana growers (N = 491) in four villages, to evaluate the roles that extension agents and farmers play in knowledge networks. Based on the structural analysis of both networks, the mechanism to integrate the informal into the formal AKIS network is discussed.

1.4 Research questions

In this research, I seek to identify the factors for improving the provision of advice to farmers, particularly the flow of knowledge regarding innovation in BXW prevention and control in Rwanda. Rogers (2003) theory of the diffusion of innovation informs this study, particularly the fact that innovations are quickly adopted when they fit well with existing social values and practices. Individual characteristics and the farming context have significant implications for farmers' adoption behavior. Based on social embeddedness theory, it is argued that the decision of an individual, for example, to adopt or reject an innovation, is driven by the social relations within which the individual operates (Zheng et al., 2022). To account for this fact, this study uses a farm typology approach and a proximity approach. The main idea is that farmer types develop the closeness of interpersonal relationships and social ties to exchange information and ideas.

The main research question that this study will investigate is as follows:

How do we reach banana farmers to provide advice promoting agricultural production in the smallholder farming context of Rwanda?

Specifically, the question has two sub-questions:

i) What are the main variables distinguishing banana growers in different farm types in Rwanda, and how does this influence farmers' decision-making processes in adopting new practices?

ii) What role do proximity dimensions play in the diffusion of knowledge within formal and informal farmer advisory networks?

Figure 1.1 presents a conceptual framework of factors that can hamper or advance the knowledge transmission to and among banana farmers in Rwanda. Distance and accessibility of a farmer are the main factors that could influence the provision of agricultural advisory to farmers by official extension agents, referred to as the formal knowledge network. Farming context and socio-economic settings translated into farm types are factors hypothesized to influence both formal and the informal knowledge networks. Farm types are also considered to be a way of specialization, thus, a proxy for cognitive proximity. Factors that are hypothesized to influence farmers' interactions, referred to as the informal knowledge network, are social embeddedness, geographical location, and knowledge. These factors are, in one way or the other, related to proximity dimensions. Concerning the formal knowledge network, the proximity dimension studied is the geographical distance and the accessibility of a farmer (geographical proximity), whereas for the informal knowledge network, in addition to geographical proximity, the effects of social and cognitive proximity are evaluated.

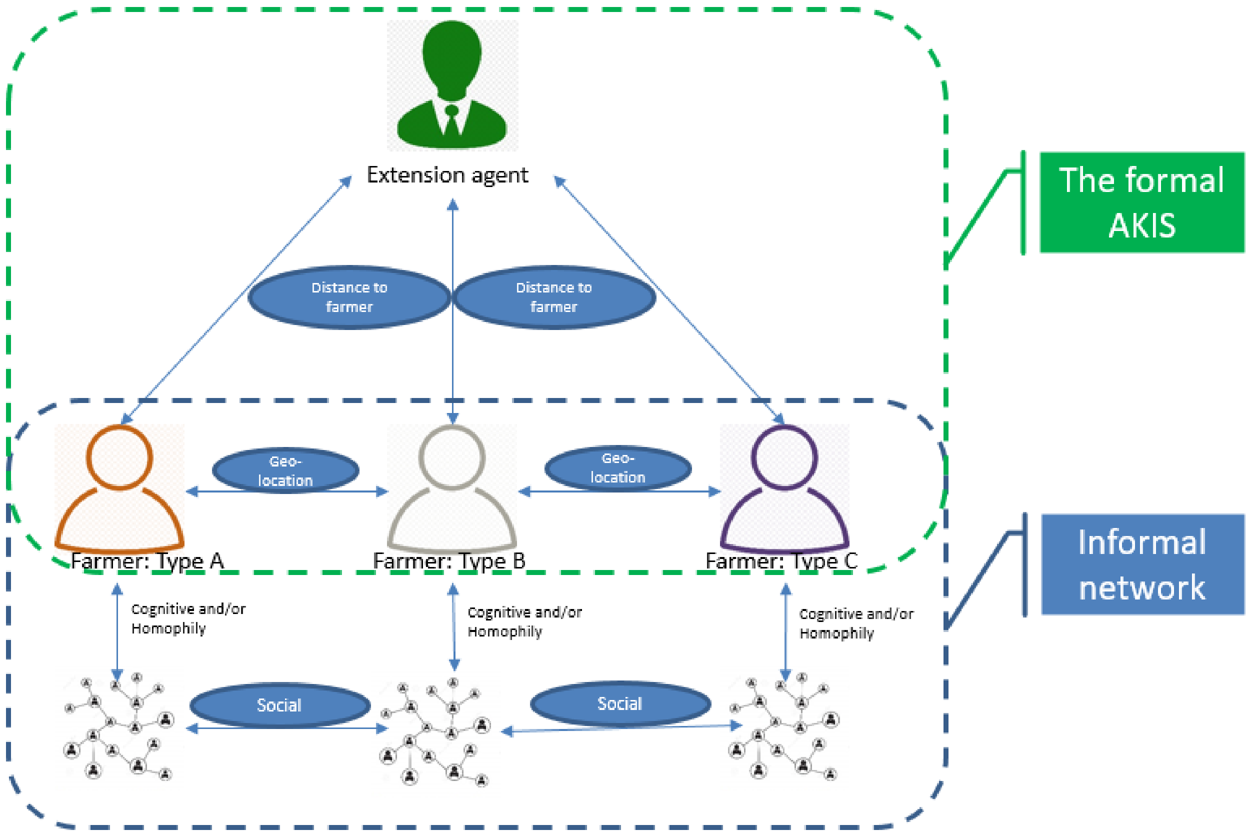

Figure 1.1: Conceptual framework for factors affecting interactions in sharing information

1.5 Structure of the thesis

Figure 1.2 presents the structure and sequencing of this thesis. The background information section presents the general introduction, the theoretical framework, gaps in the literature, and research questions that the researcher seeks to respond to. In section II, a general methodology and the case selection are presented, as well as how data were collected and analyzed.

Chapters 3 to 6 are interrelated but have been developed as separate papers. Section III focuses on the question of what the main variables are distinguishing banana growers into different farm types in Rwanda and how this influences farmers' decision-making processes in adopting new practices. This chapter uses an exploratory PCA and hierarchical cluster analysis (HCA) to identify variables distinguishing banana growers into different farm types in Rwanda and applies a regression analysis for a deeper understanding of how this influences farmers' decision-making processes in adopting new practices. Section IV uses farm types as a proxy for cognitive proximity together with social network information to evaluate how these different forms of proximity influence the diffusion of knowledge, specifically, knowledge about BXW management innovations in Rwanda. In this chapter, the informal knowledge network (between farmers) is distinguished from the official government extension system—the formal knowledge network.

Chapter 7, in section V, presents the general discussion and conclusions. It discusses the most important research findings, limitations and future outlook, and policy recommendations.

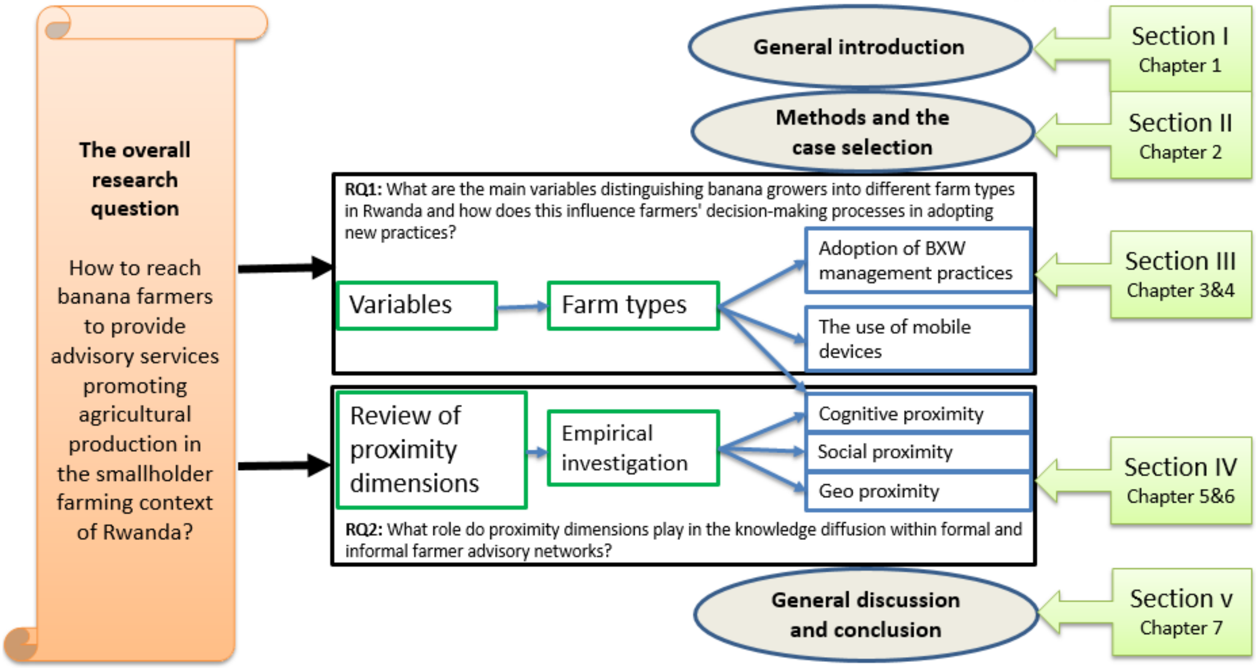

Figure 1.2: Structure of the thesis

Section II: Methods

2. Methodology

In this research, a multidisciplinary combination of research methodologies was used to obtain and analyze data for answering the research questions and to test the hypotheses. This chapter highlights the general approach used to respond to the broader research question, introduces the study area and the selection of case studies within the study area. A general overview of the data analysis methods is also provided. However, an elaboration of the specific methodology into different variables to deal with a specific research question is presented in each chapter individually.

2.1 Study area

This study was performed in Rwanda, a country in East-Central Africa between latitudes 1°04’ and 2°51’ South and longitudes 28°45’ and 31°15’ East. Agriculture is one of the most important pillars of economic growth for Rwanda, contributing about 28% to GDP and employing about 69% of the total population (Yongabo & Göktepe-Hultén, 2021). Rwanda’s principal crops include bananas, cassava, maize, beans, soybeans, Irish potato, wheat, rice, an export crops including tea, coffee, and pyrethrum. About 61% of Rwandan soil is suitable for agriculture as the soils are fertile. According to Verdoodt & Van Ranst (2003) banana is well grown in all agroecological zones, but the Mayaga and Bugesera Periphery have been identified as highly suitable, while others are low to medium suitable for Banana. Figure 2.1 presents locations of surveyed villages.

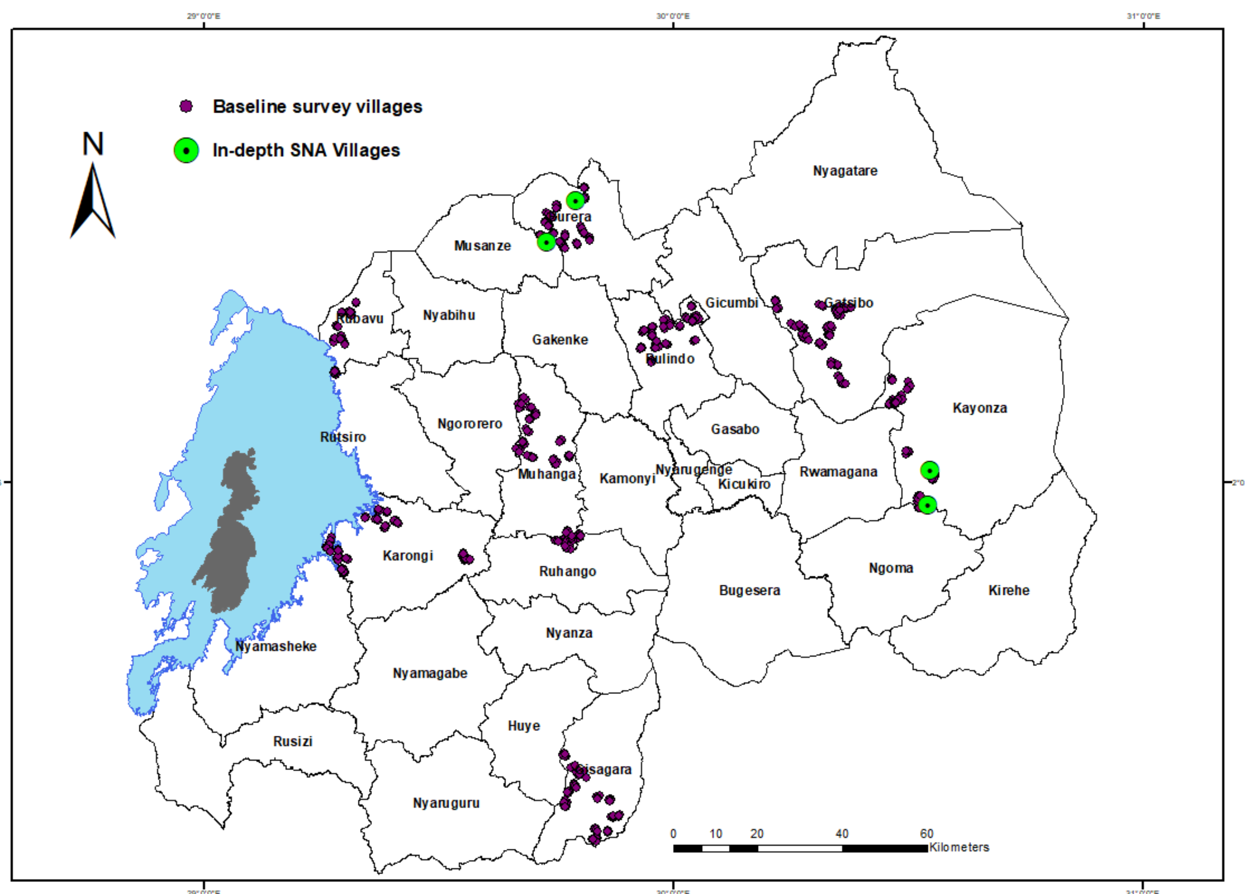

Figure 2.1: Locations of surveyed villages

In Rwanda, the extension system is characterized by a combination of different extension models including the private sector extension approach. Through the MINAGRI, the government of Rwanda established a national agricultural extension strategy in 2009. Specialized agriculture and increased agricultural productivity through increased adoption of improved technologies and professionalization of producers are the main aims of the strategy (MINAGRI, 2009). The Rwanda Agriculture Board has established the Twigire Muhinzi extension model, a community-based extension system. The model combines two approaches, namely FFS and farmer promoters (FPs), whereby an FFS facilitator mobilizes farmers in an FFS group around a field school while the FP organizes farmers in a Twigire group around a demo plot (Kantengwa & Giller, 2017). The FFS facilitator and the FPs are identified from farmers and equipped with different levels of training by RAB, which is why the approach is called farmer-to-farmer extension.

2.2 Case selection

BXW is a highly transmissible banana disease (Uwamahoro et al., 2019). Since the first report of *Xanthomonas* wilt, scientists in agronomy have identified effective BXW control methods to eradicate the disease; however, the effective methods have not been widely adopted among farmers in Rwanda (Blomme et al., 2021). Although the MIAGRI has organized several campaigns to raise awareness among farmers to combat the disease through the Rwanda Agriculture Board and in collaboration with local governments and other stakeholders, it is still popping up in the same and different areas (McCampbell et al., 2018). Given the important place that bananas occupy in the food security of the country and in farmers' livelihoods, BXW is a highly relevant case to study the effectiveness of the advisory system. The fact that the disease typically spreads from neighboring fields and through the foraging of local animals makes it very likely that neighboring farmers interact. Both the farmer who has an infected field and those who do not are all at risk, and it is expected that the flow of information about BXW will use both informal and formal knowledge networks.

2.3 Data gathering

This research used a mixed-methods approach including qualitative and quantitative data collection. A large survey conducted in 138 representative villages, which considered all agroecological zones where banana is produced, provided socio-economic baseline information. From 138 villages, four villages were selected to collect detailed information on social networks. See Figure 2.1.

2.3.1 Data for baseline information

Household information for the baseline survey was collected in eight districts (Burera, Rulindo, Gatsibo, Kayonza, Gisangara, Muhanga, Karongi and Rubavu). These districts were purposively selected for their representation of the major agroecological zones as well as their representation of different types of banana-producing farmers, within four provinces in Rwanda. Stratified sampling was used to select villages, strata being the distance from the district extension office and the incidence of BXW. The sampling team aimed to select villages with a minimum distance of 5km between two selected villages. The expected number of respondents was 720, but only 690 farmers were interviewed. The reason for this difference was the lack of villages that fall within the category of a long distance to the district headquarters in the Rubavu District, thus reducing the number of villages from 144 to 138.

2.3.2 Data for social network analysis

An in-depth social network survey was conducted in two districts, namely the Kayonza district from the Eastern Province and the Burera district from Northern Province of Rwanda. In each district, two villages were selected by their distance from extension services. In each selected village, an attempt was made to interview all banana growers. This is important because in social network analysis, a low response rate might result in a loss of relevant information on a network. Table 2.1 shows the number of interviewed farmers in each of the four villages. Social network data to form the informal social network consisted of responses to two main questions: (i) from whom have you received advice regarding BXW management? (ii) To whom have you provided advice regarding BXW management? Information regarding advisory services provided by the government formal extension system was collected as a response to the question "From which extension agent did you receive advice regarding BXW management?"

Table 2.1: Selected villages and the number of interviewed respondents

District	Sector	Cell	Village	Number of interviewed farmers
Burera	Kinoni	Nkumba	Karambo	89
	Kinyababa	Kaganda	Murambo	97
Kayonza	Kabarondo	Kabura	Rubira	91
	Kabarondo	Rusera	Rusera	214
Total				**491**

2.4 Data analysis

In this research, a combination of PCA and cluster analysis was used to develop a farm typology of banana growers. Then, different adoption behaviors were regressed to farm types to explore the relationship between dichotomous (binary) dependent variables and identified farm types as explanatory variables. To evaluate the existing collaboration and knowledge networks for BXW control and prevention in Rwanda, exploratory social network analysis in combination with ERGMs were applied.

2.4.1 Principal component analysis

A PCA was used to identify variables explaining farm differences and components to be used in grouping farmers into clusters. PCA is a data reduction method unmasking the hidden structures in a dataset through orthogonal transformation (Barnes et al., 2011; Kourti, 2009). In general, to reduce the dimension from d features to k, where k is typically much smaller than d, assuming (for example) n measurements on a vector $\mathbf{x}$, the PCA finds the linear combinations of $\phi_1\mathbf{x}, \phi_2\mathbf{x}, \ldots, \phi_k\mathbf{x}$, called principal components, that successively have maximum variance for the data, subject to being uncorrelated with previous $\phi_k\mathbf{x}$. In this case, the vector $\phi_1\mathbf{x}, \phi_2\mathbf{x}, \ldots, \phi_k\mathbf{x}$ s are the eigenvectors of the data covariance matrix, corresponding to the k largest eigenvalues (Caprihan et al., 2008). The covariance matrix is explained by the following equation:

$$S = \frac{1}{N}\sum_{n=1}^{N}(x_n - \overline{x})(x_n - \overline{x})^T$$

Eigenvectors are a special type of vector that fulfill the equation

$$\mathbf{A}\vec{v} = \lambda\vec{v}$$

where $\mathbf{A}$ is a matrix, $\vec{v}$ is a non-negative vector, denoted as eigenvector ($\vec{v} \neq \vec{0}$) and λ is a scalar ($\lambda \in \mathbb{R}$), denoted as eigenvalue (Hartmann et al., 2018).

2.4.2 Cluster analysis

To group farmers into types, clustering was performed using a hierarchical method resulting in a tree-like structure called a dendogram, and clusters are formed by connecting a k+1 cluster solution into two clusters using group resemblances (Murtagh & Contreras, 2012). With hierarchical clustering, objects or records that are close to one another are grouped together by repeated calculation of distance measures between objects (Köhn & Hubert, 2014). In general, the initial data for the HCA of N objects is a set of N*(N-1)/2 object-to-object distances and a linkage function for computation of the cluster-to-cluster distances.

2.4.3 Regression analysis

We applied the regression analysis to infer the relationship between our outcome variable and our independent variable (farm types). The outcome variables consisted of adoption of different innovation practices (BXW management options and the use of mobile phones in agriculture) as detailed in chapter 3. Since our outcome variables were recorded as binary (dichotomously coded as 0 or 1), we applied binary logistic regression analysis (Sperandei, 2014). This type of regression is the most used statistical method to predict the probability of occurrence of a binary event utilizing a logit function (Rutebuka et al., 2019).

The formula for binary logistic regression, as specified by Karasmanaki et al. (2019), is as follows:

$$f(\mathrm{Z}) = \frac{e^{\beta_0+\beta_1X_1+\beta_2X_2+\cdots+\beta_kX_k}}{1+e^{\beta_0+\beta_1X_1+\beta_2X_2+\cdots+\beta_kX_k}} = \frac{1}{1+e^{-\beta_0+\beta_1X_1+\beta_2X_2+\cdots+\beta_kX_k}}$$

where Z is the input variable and $f(\mathrm{Z})$ is its outcome, β_0 is the intercept of the regression line and β_1, β_2, …, β_k are the coefficients of independent variables X_1, X_2, …, X_k.

2.4.4 ERGMs

An ERGM was applied to test propositions regarding the influence of proximity dimension in the informal network. This model, sometimes referred to as the p* class of models (Robins et al., 2007), is a statistical model for analyzing data about social networks to understand the determinants leading to the network structure and tie formation. It is a practical model to scrutinize multilevel and multi-theoretical hypotheses for the occurrences of ties in a network (Robins et al., 2007). ERGMs have been used extensively in economic geography (Abbasiharofteh & Broekel, 2020; Hermans, 2021), but have also been used in studies on agricultural innovation networks (Hermans et al., 2017b). The main idea of ERGMs is to detect the factors that maximize the probability of tie formation with the defined structural properties of the observed network. This is done by modeling possible links between network actors as stochastic variables within an adjacency matrix. In this case, the network is regarded as one realization from many potential networks, whereas the response variable is considered as the probability of matching the observed network. ERGMs fit broadly within the same exponential family of statistical models as conventional generalized linear modeling approaches (Robins et al., 2007). According to Stivala & Lomi (2021) an ERGM can be summarized mathematically as follows:

$$Pr(X = x) = \frac{1}{\kappa(\theta)} \exp(\sum_{A} \theta_A z_A(x))$$

where $X = [X_{ij}]$ is a 0–1 matrix of random tie variables, *x* is a realization of *X*, *A* is a “configuration”, a (small) set of nodes and a subset of ties between them, $z_A(x)$ is the network statistic for configuration *A*, θ_A is a model parameter corresponding to configuration *A*, $\kappa(\theta)$ is a normalizing constant to ensure a proper distribution.

Given an observed network *x*, the aim is to find the parameter vector θ that maximizes the probability of *x* under the model. Then, for each configuration *A* in the model, its corresponding parameter θ_A and its estimated standard error allow inferences about the over- or under-representation of that configuration in the observed network. If θ_A is significantly different from zero, then if θ_A > 0, and configuration *A* is over-represented or under-represented, θ_A<0.

2.5 Concluding remarks

This chapter contains an overview of how data were gathered and the general analysis undertaken in this thesis. Specific methodologies, variables, reasons for selecting a particular approach, and how specific research questions were answered are elaborated in depth from chapter 3 to chapter 6.

Section III: Farm heterogeneity and decisions to adopt agricultural technology

This section is based on two papers:

The use of mobile phones and the heterogeneity of banana farmers in Rwanda, by Michel Kabirigi, Haruna Sekabira, Zhanli Sun & Frans Hermans, published in Environment, Development and Sustainability (2022), https://rdcu.be/cLzJR, DOI: https://doi.org/10.1007/s10668-022-02268-9.

Using farmer household typologies to understand the Banana Xanthomonas Wilt (BXW) management in Rwanda, by Michel Kabirigi, Frans Hermans, Zhanli Sun, Svetlana V. Gaidashova, Mariette McCampbell, Julius B. Adewopo, Marc Schut, under review in NJAS – the Wageningen Journal of Life Sciences

3. The use of mobile phones and the heterogeneity of banana farmers in Rwanda

Abstract

Information and communications technologies (ICTs) play a key role in improving agricultural production, enhancing socio-ecological resilience, and mitigating rural poverty. However, the use of ICTs for agricultural development among smallholder farmers, especially in the least developed countries, still lags behind. It is therefore critical to understand distinct attitudes among heterogeneous smallholder farmers that determine the use of ICTs, such as mobile phones. Moreover, data-driven empirical studies on the use of mobile phones in smallholder settings are still scarce. We bridge this knowledge gap by evaluating the link between the use of mobile phones and various farming types of smallholder farmers in Rwanda. Using the principal component and cluster analysis, we analyzed 690 banana-farming households across eight of the 10 major agro-ecological zones of Rwanda and developed a typology of banana farms. We identified three distinct farm types based on a combination of various farmer characteristics and farm operations and endowments, namely the beer banana, livestock-based, and the cooking banana farm types. These farm types clearly differ in terms of ownership and use of both basic and smart mobile devices. Farmers in the cooking banana farm type are far more likely to own and use smart mobile phones than in other types. Regression results further indicated that farm type, gender, and education have significant correlations with the perceived usefulness of mobile phones in agriculture. Major barriers to using ICT-based agricultural services were i) low awareness of the existence of ICT services, ii) limited availability of ICT services, iii) lack of technical know-how, iv) relatively high prices of ICT devices, and v) low levels of ICT literacy. This empirical study provides strategically important insights into the transition to digital agriculture in the context of smallholder farming systems.

Keywords: ICTs, mobile phone, agricultural extension services, small farmers, banana production

3.1 Introduction

Given the increasing demand to feed the world's rapidly growing population, ensuring sustainable agricultural development is crucial and indispensable. More so that the increase in crop yield does not rise at the same pace as the increase in food demand (Long et al., 2015). However, the effectiveness of several sectors is essential in ensuring sustainable agricultural development. For instance, communication, transfer of knowledge, and information exchange have played a significant role in the agricultural advancement from traditional to modern systems, and such advancements are expected to foster the agricultural transformation toward sustainable food systems (El Bilali & Allahyari, 2018; Zhang et al., 2016). Moreover, information and communication technologies (ICTs) can help boost efficiency and sustainable agricultural production by providing dynamic, reciprocal, and effective information exchange regarding agriculture-enabling innovations (El Bilali & Allahyari, 2018; Klerkx et al., 2019a; Munthali et al., 2018; Zhang et al., 2016). With the term *innovation*, we refer to the successful combination of new technologies or tools (hardware), new knowledge or new modes of thinking (software), and the reordering of institutions and of organizations (orgware) (Awan et al., 2021; Cheng et al., 2021; Hermans et al., 2017b).

ICTs today play an integral role directly or indirectly in agricultural and rural development by improving productivity, enhancing food security, and improving farmers' livelihood and general welfare (Sekabira & Qaim, 2017). ICTs can particularly improve communication and information access among actors along agri-food supply chains and other stakeholders, thus making development inclusive even for those who are located remotely. Smallholder farmers can benefit from ICTs, especially internet infrastructure and mobile phones, which provide farmers with opportunities to easily access technological innovations, extension services, markets, and essential weather information (Debsu et al., 2016). From this perspective, it is argued that the use of mobile phone-based ICT platforms is also a potential way to reorganize and facilitate formal agricultural extension by delivering relevant, timely, and cost-effective information (Duncombe, 2016; McCampbell et al., 2018; Schut et al., 2016) and improve communication among farmers in the context of informal knowledge sharing networks (Vouters, 2017).

Although the literature presents a wide range of benefits of using mobile phones in agriculture, they do not guarantee the adoption of mobile-based technologies among farmers, particularly in smallholder farming systems, which still dominate in underdeveloped and developing countries. Failure to take into account the heterogeneity of farmers, especially smallholder farmers, has been identified as one of the potential barriers to innovation adoption (Coe et al., 2016; Hammond et al., 2017). Various studies in Sub-Saharan Africa have exposed high levels of variability among smallholder farmers in many characteristics, such as cropping, farm size, soil fertility, livestock assets, education, labor availability, and sociocultural traits (Bidogeza et al., 2009; Kansiime et al., 2018; Nabahungu & Visser, 2011; Tittonell et al., 2005). This variability results in diverging priorities that correspond to various behaviors concerning innovation adoption (Nabahungu, 2012; Tittonell et al., 2007).

Therefore, farm heterogeneity has a profound implication on farm households' efficiency and needed policy interventions. On one hand, the one size fits all scaling approach, in which technologies are packed in one adoption package regardless of particular compatibility and risk aversion imposed by particular contexts of these diverse (heterogeneous) farms, is increasingly questioned (Cleary & Van Caenegem, 2017; McCampbell et al., 2018; Officer et al., 2015). On the other hand, policies and measurements cannot be designed on an individual basis alone. This would be too time-consuming and costly.

This means that although heterogeneity among farmers needs to be considered, the common features among groups of farmers are also important in the design of communally feasible and targeted interventions. As a result, farm and farmer typologies have become increasingly popular. Typology construction is an efficient method to understand farmer diversity by delineating groups of farmers with common characteristics while considering general farmers' diversity and heterogeneity (Shukla et al., 2019). Farmer typology studies have been used to classify farm households based on socioeconomic characteristics to understand how they would change with the adoption of innovations based on their diverging priorities (Bidogeza et al., 2009; Hammond et al., 2017).

The most recent studies on the heterogeneity of farmers' adoption behaviors regarding the use of mobile phones have been mainly econometrics-based (i.e., regressions on farmers' characteristics;(Adegbidi et al., 2012; Islam & Grönlund, 2011; Tadesse & Bahiigwa, 2015). However, farmers' preferences have to be regarded in the context of the broader agricultural innovation systems (Martin-Collado et al., 2015). Instead of a narrow socioeconomic farmer typology, a broad typology in which farms and farmers are investigated together could be a starting point in predicting farmers' preferences regarding the adoption of mobile phones.

Therefore, to address this research gap, we take a broad farm and farmer typology approach to provide empirical evidence of links between mobile phone-based information delivery and farm diversity in the context of banana farmers in Rwanda. This study's contribution is twofold. First, we link farm heterogeneity with the use and perception of mobile phones in the context of smallholder farmers. Second, we provide a practical tool for projects intending to use mobile phones in agricultural production in a smallholder context. Specifically, we respond to the research question, "What combinations of farm/farmer types can be differentiated when it comes to the ownership and use of mobile devices?" In this case, we distinguish a farm typology (that contains various farm types based on farm characteristics, such as production system) and a farmer typology (that contains various farmer types based on farmers' characteristics, such as gender and age).

In the subsequent theoretical section, we start with a review of the farm heterogeneity perspective. In the next section, we explore the literature on the heterogeneity of farmers themselves and link them to the potential of using mobile phones to support agricultural information sharing. In the methodology section, we go deeper into the case of Rwanda, including the data gathering and processing approach. The results section presents identified farmer typologies that we link to the use of mobile phones in discussions. We also make concluding remarks at the end.

3.1.1 Farm heterogeneity perspective

The agricultural sector has experienced substantial structural changes in terms of farm size, farm fragmentation, and farming system diversification (Sevik et al., 2021). These structural changes have significant effects on productivity and farming efficiency (Chavas, 2001). Jackson-Smith (1999) and Saint-Cyr (2017) showed that accounting for heterogeneity may be crucial to fully understand the structural changes in farming because they stem from individual farmers' decisions. Farms' heterogeneity leads to multifaceted agricultural systems, thereby complicating the scaling of agricultural innovations (Weersink, 2018). The diversity in farms and farming systems also extends to the type of technologies employed on these farms. Large export-oriented farms will employ more capital-intensive technologies, but on small subsistence farms, manual labor and simple tools will more often be used. The fact that farms are heterogeneous, even within the context of the smallholder farming system of Africa, has been well documented (Bidogeza et al., 2009; Nabahungu & Visser, 2011; Tittonell et al., 2005).

In this study, we assume that ICT-based tools and mobile phones can also be viewed as a kind of production technology, as we hypothesize that

H1: Farm types are distinct and differentiated by the use of both basic and smart mobile devices, Although Folitse et al. (2019) and Hoang (2020) have discussed the pros and cons of farmers using mobile phones, studies differentiating between the use of basic and smart mobile phones are scarce. It is very important to differentiate basic mobile phones from smartphones, especially in developing countries, for several reasons, especially regarding subsistence smallholder farmers. Smartphones, in addition to being expensive compared to basic phones, are also regarded as miniature computers that can place and receive calls, therefore requiring a certain level of ICT literacy. This fact implies that smartphones might be used for functions other than mere communication, such as security, financial transactions, internet browsing, and video conferencing. All these functions require a relatively higher literacy skill to operate. Basic phones, on the other hand, are cheap and easy to operate and can satisfy the need of getting in touch through simple calls and messaging.

3.1.2 Determinants of farmers’ mobile phone use

The upsurge in empirical studies provides insights into the factors that determine the use of mobile phones. Transactions costs, perceived profitability, credit constraints, operational skills, the high price of mobile phones, and network failure are mentioned as bottlenecks hindering the use of mobile phones, the main form of ICT, in agricultural production (Abay et al., 2016; Folitse et al., 2019; Minten et al., 2013). Some determining factors discussed in the literature are presented as limiting factors. However, it is crucial to understand that cases in developed countries might be far different from those in developing countries. For example, farmers in Ghana indicated network failure and the high price of mobile phones were the largest hindrances to mobile phone use (Folitse et al., 2019), but in Germany, computer literacy is one of the most important predictors of smartphone use in agriculture (Michels et al., 2020). Regarding determinants of mobile phone use, Folitse et al. (2019) showed a significant association between mobile phone use and demographic variables such as age, education, gender, and land size. Tadesse and Bahiigwa (2015) and Muto and Yamano (2009) also showed that younger and educated farmers are more likely to own and use mobile phones in agriculture than older and relatively low-educated farmers. Folitse et al. (2019) and Michels et al. (2020) agreed that older farmers were less likely to own and use mobile phones and more educated farmers were more likely to own and use mobile phones, because younger generations were more interested in new technologies and educated farmers could easily acquire basic ICT operational skills. Muto & Yamano (2009) showed that in Uganda, telecommunication companies establish mobile networks more often in big cities, where the economy is advanced and the population density is high, indicating that economic status and household income are among the most important determinants for owning and using mobile phones in developing countries. The household behavior theory suggests that household decisions are described by a utility function, which is maximized for farm production and cash flow constraints (Arthur & van Kooten, 1985; Lancaster, 1975). With this theory in mind, we formulated two more hypotheses:

H2a: *Farmers with higher income and more education are likely to own and use mobile phones.*

H2b: *Younger farmers are more likely to own and use mobile phones.*

3.2 Methodology

3.2.1 Study area, sampling, and data

We conducted this study in Rwanda, East Africa. We used data from a household survey that trained enumerators conducted from July to August 2018. We collected farmer-household information through the survey using a structured questionnaire in eight districts: Burera, Rulindo, Gatsibo, Kayonza, Gisagara, Muhanga, Karongi, and Rubavu. Following a stratified sampling approach, we purposively selected these districts for their representation of the major agro-ecological zones and of various types of banana-producing farmers within four provinces in Rwanda. We selected districts based on expert knowledge (mainly through multiple consultations with the banana program leader at the Rwanda Agriculture and Animal Resources Development Board (RAB) and raw data from a countrywide rapid assessment of Banana Xanthomonas wilt (BXW) status, which the RAB conducted between 2017 and 2018. Figure 3.1 summarizes districts' coverage of the main agro-ecological zones, and Table 3.1 summarizes the area covered by bananas in respective districts. We selected sectors and cells, low-level administrative units, based on expert input from the district and sector agronomists. The sampling team aimed for the selection of villages within a minimum distance of 5 km. As a result, we interviewed 690 farmers from 138 villages.

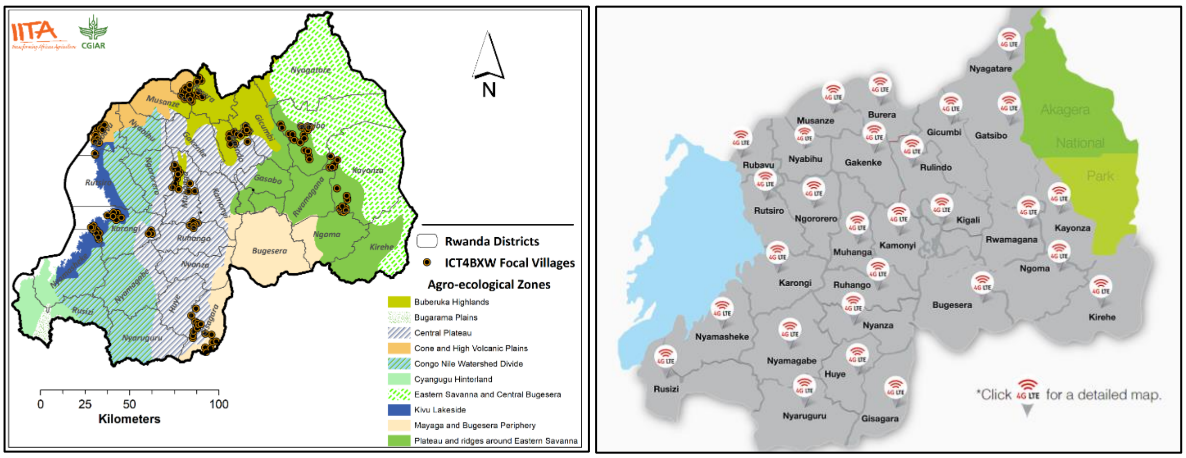

Figure 3.1: Study area and network coverage maps (*https://www.ktrn.rw/coveragemap*)

Table 3.1: Main characteristics of studied districts

District	Cultivated area (ha)	Total B. area (ha)	C.B. Area (ha)	B.B. Area (ha)	Prop. Banana land (%)
Burera	28100	2341	806	1317	8,3
Rulindo	25146	7835	1613	4182	31,2
Gatsibo	52860	16307	8365	5227	30,8
Kayonza	48857	15318	11540	2497	31,4
Gisagara	28867	9802	2146	6218	34,0
Muhanga	30565	13394	1760	9051	43,8
Karongi	21361	8465	797	6793	39,6
Rubavu	17153	953	683	187	5,6

Key: *B. = Banana, C.B = Cooking banana, B.B. = Beer banana, Prop. = Proportion of land allocated to bananas over the total cultivated area. source: (NISR, 2017)*

Most questions in the questionnaire were closed-ended questions, such as multiple-choice and numerical questions. The questionnaire covered a wide range of categories of variables, such as socioeconomics, production systems, advisory services, and ICT in agriculture. For this study, we used data related to socioeconomic characteristics of farmers, banana production system characteristics, and extension services to develop farmer typology. At the same time, we used variables such as ownership and use of mobile phones, the relevance of ICTs in BXW management, and challenges farmers face in using ICTs in agriculture to describe the use of mobile phones among farmers, hypothesized to be affected by farmers' heterogeneity, recapitulated in the farm typology.

To develop farm typology, we started with around 60 variables selected based on the literature review and expert judgment, which is the most common method used when deciding which raw variables to start with (Bidogeza et al., 2009). We then subjected selected variables to further filtering in three steps to identify variables contributing most to the variance. The first step was to identify highly correlated variables. Once we found them, we removed them, as they carried redundant information (Alvarez et al., 2014). The second step was to identify possible outliers in the dataset by plotting out boxplots and histograms. We determined whether the identified outliers were outstanding values or typing errors and then dealt with them accordingly. The third step was to identify variables possibly measuring the same thing by determining whether they had the same sign in various components. We conducted a principal component analysis (PCA) and determined between the two correlated variables the one with less contribution to the first five components. The screening of variables was systematic; that is to say, we removed one variable at a time and then conducted another PCA to observe changes. We identified 12 variables as most contributing to the heterogeneity of banana farmers (Table 3.2).

Table 3.2: Variables selected to be included in the PCA

Variable	Units	Average
Tropical livestock unit	Number	0.94±0.91
Income from banana	Rwandan Francs*1000	70.2±52.7
No. of people talked to about BXW	Number	10.7±8.87
Nutrition diversity	Number	5.15±1.98
Number of extension visits	Number	1.55±0.82
Education years	Number	6.06±3.34
Proportion of:		
Land allocated to cooking bananas	Percentage	14.4±24.6
Cooking bananas consumed	Percentage	17.7±32.2
Cooking bananas sold	Percentage	12.5±25.7
Land allocated to beer bananas	Percentage	22.2±28.5
Beer bananas consumed	Percentage	7.9±22.3
Beer bananas sold	Percentage	38.4±45.3

*the average value of income from bananas is to be multiplied by 1000 (70,200±52,700 Rwandan Francs)

As key target variables, we collected data related to the use of mobile phones using three questions: 1) “What type of mobile phone do you own?” followed by “What type (smart type, basic type, or none) of mobile phone did you use in the past three months?” 2) “What barriers (awareness of existence of ICT-based agricultural services=awareness, ICT-based agricultural services not available=availability, not know-how to use ICT-based agricultural services=know-how, ICT-based agricultural services not in local language=language, low literacy level=literacy, mobile devices and ICT-based agricultural services being expensive=expensive, and others) do you experience when using ICT-based agricultural services? 3) “How useful (neutral, not useful, somewhat not useful, somewhat useful, very useful) is the use of these mobile services currently for your work as a banana farmer?” Table 3.3 summarizes the responses concerning the use of mobile phones among interviewed farmers. We also collected data on other socioeconomic variables, such as gender, age, and education.

Table 3.3: Summary of the use of mobile phones among farmers

Type of variable	Name of variable	Categories	Frequency	% of respondents
Ownership	**Own smartphone**	Yes (= 1)	30	4.3
		No (=0)	660	95.7
	Own basic phone	Yes (= 1)	494	71.6
		No (=0)	196	28.4
	No phone	Yes (= 1)	190	27.5
		No (=0)	500	72.5
Use	**Used smartphone**	Yes (= 1)	27	3.9
		No (=0)	663	96.1
	Used basic phone	Yes (= 1)	550	79.7
		No (=0)	140	20.3
Barriers to the use of ICT-based agricultural services	**Awareness**	Yes (= 1)	360	52.2
		No (=0)	330	47.8
	Availability	Yes (= 1)	37	5.4
		No (=0)	653	94.6
	Know-how	Yes (= 1)	256	37.1
		No (=0)	434	62.9
	Language	Yes (= 1)	25	3.6
		No (=0)	665	96.4
	Literacy	Yes (= 1)	36	5.2
		No (=0)	654	94.8
	Expensive	Yes (= 1)	91	13.2
		No (=0)	599	86.8
	Others	Yes (= 1)	119	17.2
		No (=0)	571	82.8
Usefulness	**Usefulness**	Not useful (=1)	79	11.4
		Somewhat un-useful (=2)	24	3.5
		Neutral (=3)	123	17.8
		Somewhat useful (=4)	368	53.3
		Very useful (=5)	96	13.9

This study targeted banana farmers distributed in contrasting agro-ecological zones (Figure 1). Most (53%) farmers were between 25 and 50 years old. Most respondents were male (60%) and married (84%), with a mean household size of five people. Most respondents (68%) had also attained a primary level of education. Furthermore, most respondents (80%) owned basic phones, and only 4% owned smartphones. Most respondents (70%) did not have off-farm income sources, and 44% solely grew bananas as crops. Regarding the grown banana types, 82% grew at least some cooking bananas on their plantation, and 57%

grew some beer bananas. In terms of livestock endowment, 64% of farmers had cattle, 43% had goats, 21% had pigs, and 35% had chickens. Farmers may have several types of bananas and livestock animals.

3.2.2 Principal component analysis and cluster analysis

We used exploratory PCA and hierarchical cluster analysis to develop farm typologies with selected variables. We applied the Kaiser rule, which says that retained components are those with eigenvalues (λ) > 1 (Jackson, 1993), to identify principal components and conduct further cluster analysis. We retained five components having eigenvalues (λ) > 1 and explaining 63.3% of the total variance. Using factor loadings, it is possible to identify variables that explain the component most and would describe it.

Figure 3.2a shows the scree plot highlighting 10 components from the 12 variables that we included in the PCA, with five components having eigenvalues greater than 1 retained for cluster analysis and explaining about 63% of the total variation. Figure 3.2b presents variables' contributions to the construction of two main components (explaining about 33% of variation) where land allocated to beer banana or cooking banana were the main contributing variables.

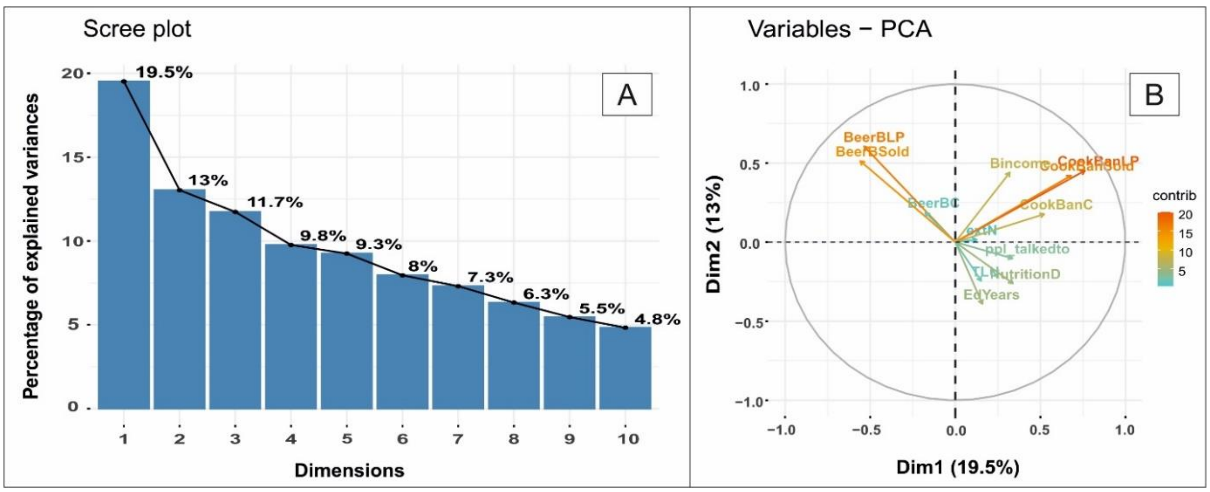

Figure 3.2: PCA Scree plot (A) and variables' contributions to components (B).

Note: NutritionD=Nutrition diversity, extN=Number of extension visits, EdYears=Education Years, TLU=Tropical Livestock Unit, CookBanLP=Proportion of land allocated to cooking banana, CookBanC=Proportion of cooking banana consumed, CookBanSold=Proportion of cooking banana sold, BeerBLP=Proportion of land allocated to beer banana, BeerBC=Proportion of beer banana consumed, BeerBSold=Proportion of beer banana sold, Bincome=Income from banana, ppl_talkedto=No. of people talked to about BXW

We subjected the five components retained to hierarchical cluster analysis. Cluster analysis is a method of grouping dataset objects into groups with similarities (Penkova, 2017). We thus generated a dendrogram (Figure 3.3a) with the sequence in which farmers were merged. The dendrogram provides a default cutting line, and it allows us to adjust the cutting lines based on the visualization, resulting in a different number of clusters. Using the default cutting line, we generated three distinct clusters, visualized in Figure 3.3b. Clusters 1 and 2 are distinct, whereas cluster 3, although distinct in particular elements, shares some characteristics with clusters 1 and 2 (Figure 2b).

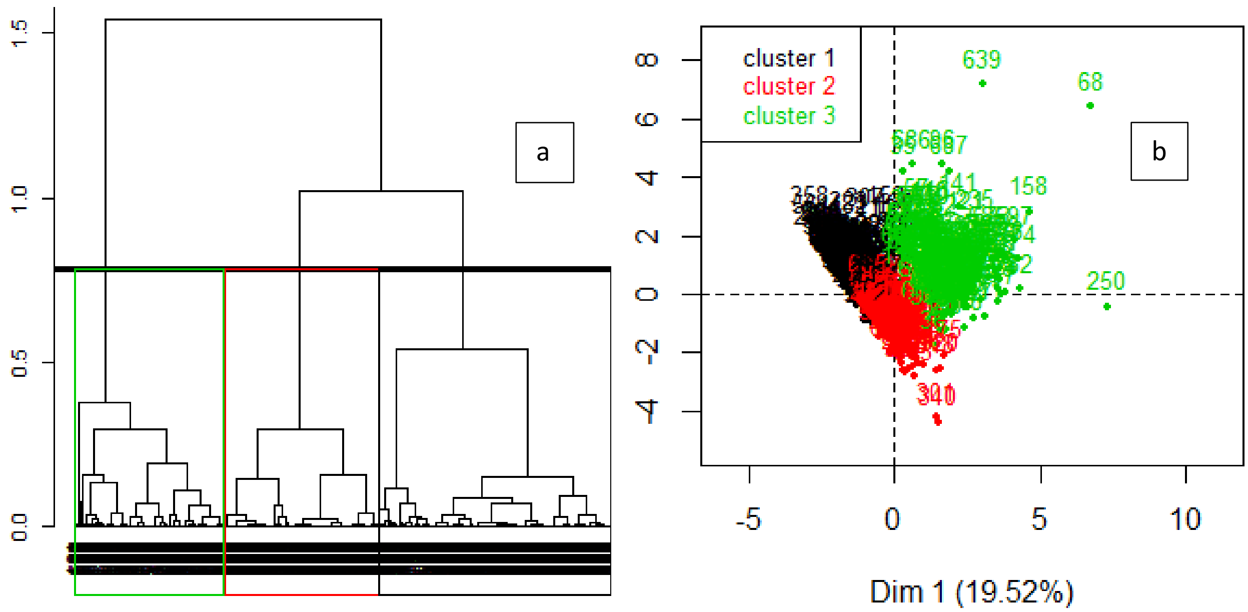

Figure 3.3: Cluster dendrogram and clusters graphic representation

3.2.3 Logistic regression models

We analyzed data using statistical package R version 4.0.3 (Kaya et al., 2019; Team, 2021). We also derived and reported descriptive statistics. To examine the relationship between the outcome variable (dependent) and predictor variables (independent), we applied logistic regression models (Menard, 2002). Logistic regression is used to obtain a statistic (odds ratio) that quantifies the strength of the association between two events in the presence of more than one explanatory variable (Sperandei, 2014). Our outcome variables were the use of mobile phones (1: using or 0: not using), barriers to the use of mobile phones (a farmer considering a certain aspect a barrier or not), and perceived usefulness of mobile phones (whether each farmer considered a specified level of usefulness sufficient or not). Our predictor variables were farm type as well as farmer's gender, level of education, level of income from bananas, and age category. The selected independent variables portray the heterogeneity among banana farmers. The nature of data (responses) dictated the type of logistic regression model that we applied. A logistic regression can be binomial, ordinal, or multinomial. Our data, as described in Section 3.3, shows that the use and barriers to the use of mobile phones are binary variables; therefore, we analyzed the data using binomial logistic regression. In this case, we coded the outcome as "0" or "1" (0 = not using, 1= using), as this coding leads to the most straightforward interpretation. This analysis allows us to estimate how perturbations in model parameters affect the probability that a certain binary outcome will occur (Morotti & Grandi, 2017). Using the outcome variable "Own smartphone" as an example, the final model is given by the following equation:

$$p_k(\text{Own smartphone}) = \begin{cases} \left(\dfrac{1}{1+e^{-z_k}}\right) \text{for Own smartphone}_k = 1 \\ \left(1 - \dfrac{1}{1+e^{-z_k}}\right) \text{for Own smartphone}_k = 0 \end{cases}$$

with

$$z_k = \beta_0 + \beta_1 \times \text{Types} + \beta_2 \text{ Gender} + \beta_3 \times \text{Education} + \beta_4 \times \text{Income} + \beta_5 \times \text{Age}$$

βi are the regression coefficients associated with the independent variables. In this case, we are modelling the outcome "own smartphone" as predicted by farm typology, gender, education, income from bananas, and age category.

Concerning the perceived usefulness of mobile phones, data were recorded as five ordinal responses; therefore, we applied an ordinal logistic regression. Results have been interpreted based on odds ratios. For estimation, we use the ordered logit model with the following structure:

$$logit\big(P(Y \leq j)\big) = log\left[\frac{P(Y \leq j)}{1 - P(Y > j)}\right]$$
$$= \alpha_j + \beta_1 \times \text{Types} + \beta_2\ \text{Gender} + \beta_3 \times \text{Education} + \beta_4 \times \text{Income} + \beta_5 \times \text{Age}$$

where Y is the response variable with j^{th} category, αj is the intercept parameter, βk are the parameters related to each explanatory variable explaining the effect of that explanatory variable on the response variable, and *P()* are the cumulative probabilities for a j^{th} category.

We used the likelihood ratio to test the goodness of fit of our models and used the dominance analysis to determine the predictors' importance in the model (Azen & Traxel, 2009).

We present odds ratios showing the probability of an event (on outcome variable) to happen compared to the selected reference group of predictor variables. Reference groups were beer banana farm type, female, none educated, farmers with zero income from bananas, and young (<30 years old) farmers for farm typologies, gender, education, level of income from bananas, and the age category of our independent variables, respectively. The likelihood ratio shows a significant improvement in the fit of the full model over the null model. In the Hosmer Lemeshow goodness of fit test, the p value of our models ranged between 0.34 and 0.99, indicating no evidence of poor fit.

3.3 Results

3.3.1 Principal component analysis and clustering results

In Table 3.4, we present identified variables associated with farm heterogeneities, which can be summarized in three groups: respondent characteristics (nutrition diversity and education years); type of banana grown, distribution in the field, and use (cooking or beer banana with their respective proportion of allocated land, banana income, and proportion sold and consumed); and access to extension services (number of extension visits and people talked to). By observing the v.test values, which indicate if the mean of the cluster is lower or greater than the overall mean, we find three farm types. Type one is more associated with the proportion of beer bananas sold, the proportion of land allocated to beer bananas, and the proportion of beer bananas consumed. Thus, we named it beer banana farm type (BBF). The second type is more associated with tropical livestock units (livestock numbers converted to a common unit), education years, and nutrition diversity. We named it livestock-based farm type (LBF). The third is named cooking banana farm type (CBF) because it is mostly associated with the proportion of land allocated to cooking bananas and the proportion of cooking bananas sold and consumed.

Table 3.4: Variables associated with farm heterogeneity and resulting clusters

Variable	V.test Mean C1	V.test Mean C2	V.test Mean C3
Nutrition diversity	-5.12	2.55	2.89
Number of extension visits	-2.02	-	-
Education years	-3.10	2.91	-
Tropical livestock unit	-2.56	3.38	-
Income from bananas	-	-4.94	5.77
No. of people talked to	-4.15	-	3.95
Proportion of:			
Land allocated to cooking bananas	-11.20	-8.38	20.62
Cooking bananas consumed	-9.13	-7.81	17.81
Cooking bananas sold	-9.60	-8.26	18.78
Land allocated to beer bananas	16.77	-12.41	-5.30
Beer bananas consumed	6.39	-5.60	-
Beer bananas sold	19.45	-14.27	-6.27
Named according to V.test	***Beer banana farm type (BBF)***	***Livestock-based farm type (LBF)***	***Cooking banana farm type (CBF)***

Figure 3.4 provides descriptions of the resulting farm types and associated variables included in regression models. Concerning education level, most farmers attained a primary level of formal education across all farm types. However, relatively more cooking banana farmers had attained secondary education. The low level of income from bananas was between 1,000 and 20,000 Rwandan francs (1 Rwandan franc = 0.00096 USD), whereas high levels were above 20,000 francs. The beer banana farm type had more high-income farmers. However, most farmers across all types did not attain cash income from bananas. This implied that most farmers were subsistence farmers who grew bananas for self-consumption. From the age category chart, the majority of farmers were older (above 50 years). On the other hand, most respondents were males, and the livestock-based farm type had fewer females than the rest of the farmer types.

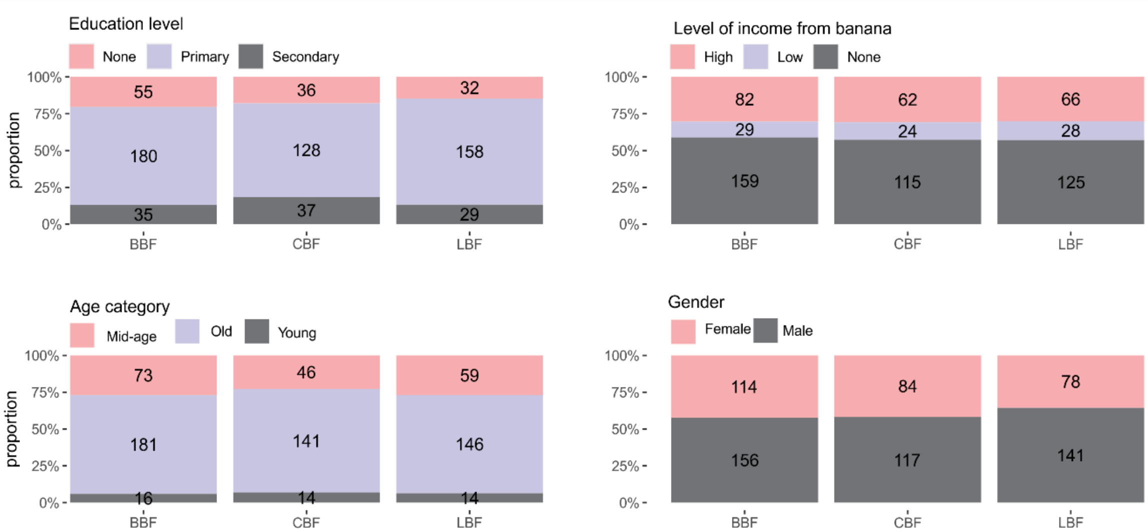

Figure 3.4: Description of households and respondents by banana farm typologies—BBF: beer banana farmers, CBF: cooking banana farmers, LBF: livestock-based banana farmers

3.3.2 Regression analysis results

In Tables 3.5, 3.6, and 3.7, we present regression results on ownership and use of mobile phones by farmer typologies (Table 3.5), barriers for mobile phone use (Table 3.6), and perceived usefulness of mobile phone-based agricultural services (Table 3.7).

3.3.2.1 Ownership and use of mobile phones

Results from Table 3.5 show that farm type, gender, education, and age significantly affected the likelihood of owning or using mobile phones. Cooking banana farmers and farmers with a secondary level of education were likely to own and use both smart and basic phones. Livestock-based, male, primary-educated, and older farmers were more likely to own and use basic phones. However, income from bananas had little effect on the likelihood of owning or using mobile phones.

Table 3.5: Odds ratios and standard error (in parentheses) for the binary logistic regression model for owning and using mobile phones

Predictor variables	Own Smart P.	Own Basic P.	No Phone	Used Smart P.	Used Basic P.
Cooking banana farm type	2.5641**	2.1174***	0.4249***	3.1237**	2.3302***
	(0.4620)	(0.2270)	(0.2339)	(0.5106)	(0.2564)
Livestock-based farm type	1.0369	1.5274**	0.6786*	1.4403	1.6554**
	(0.5376)	(0.2115)	(0.2129)	(0.5756)	(0.2332)
Male farmers	0.8008	2.1214***	0.4713***	0.7829	1.0700
	(0.3991)	(0.1856)	(0.1884)	(0.4189)	(0.2082)
Primary education	4.6078	3.1304***	0.3025***	3.8172	3.4477***
	(1.0427)	(0.2185)	(0.2198)	(1.0496)	(0.2299)
Secondary education	19.6619***	7.7792***	0.1053***	19.3225***	8.6930***
	(1.0552)	(0.3579)	(0.3776)	(1.0547)	(0.4212)
High banana income	0.7472	0.8568	1.2084	1.2811	0.7586
	(0.4675)	(0.2004)	(0.2029)	(0.4525)	(0.2204)
Low banana income	1.5315	0.6920	1.4437	1.6197	0.6727
	(0.5452)	(0.2931)	(0.2988)	(0.6073)	(0.3162)
Middle-aged farmers	4.1449	1.4949	0.6888	3.3493	1.9893*
	(1.0721)	(0.3781)	(0.3859)	(1.0971)	(0.3983)
Older farmers	1.7755	1.8765*	0.5640	1.9016	2.4066**
	(1.0540)	(0.3542)	(0.3616)	(1.0633)	(0.3713)
Constant	0.0027***	0.2814***	3.4231***	0.0020***	0.4917
	(1.4910)	(0.4187)	(0.4254)	(1.5245)	(0.4354)

Note: Variables with "*", "**", and "***" are significant at 1%, 5% and 10% significance levels.

3.3.2.2 Barriers in using mobile phone-based agricultural services

Results in Table 3.6 show that cooking banana farmers were less likely to be limited by the lack of awareness of existing mobile phone-based agricultural services and technical know-how. Farmers on livestock-based farm types were also less likely to be limited by technical know-how. Surprisingly, male farmers were more likely to be limited by the lack of technical know-how, devices being expensive, and language barriers. On the other hand, farmers with primary education were more likely to be limited by the availability of phone-based agricultural services, devices being expensive, and lack of technical know-how, yet farmers with secondary education were more likely to only be limited by devices being expensive. However, farmers with both primary and secondary education were less likely to be limited by ICT literacy levels compared to uneducated farmers. Farmers who earned high banana incomes were also less likely to be limited by ICT literacy levels and the availability of ICT services compared to subsistence farmers. On the other hand, farmers with low income from bananas were less likely to be limited by a lack of awareness of the existence of mobile phone-based agricultural services compared to subsistence farmers. Unsurprisingly, older farmers were more likely to be limited by a lack of technical know-how concerning mobile phone-based agricultural services compared to younger ones.

Table 3.6: Odds ratios and standard error (in parentheses) for the binary logistic regression model for barriers to using mobile phone-based agricultural services

Predictor variables	Awareness	Availability	Knowhow	Language	Literacy	Expense	Others
Cooking banana type	0.6848**	0.6718	0.6346**	1.4674	0.6837	0.8448	1.9338***
	(0.1901)	(0.4544)	(0.2010)	(0.4964)	(0.4539)	(0.2872)	(0.2491)
Livestock-based type	0.7453	1.0320	0.7212*	0.8269	0.9620	0.7846	1.3751
	(0.1859)	(0.3895)	(0.1927)	(0.5229)	(0.4145)	(0.2796)	(0.2580)
Male farmers	1.1226	1.5174	2.2577***	15.5018***	0.6465	3.4910***	0.5046***
	(0.1624)	(0.3917)	(0.1748)	(1.0279)	(0.3664)	(0.3032)	(0.2133)
Primary education	1.1534	7.8881**	1.6051**	4.3155	0.2101***	8.3141***	1.1157
	(0.2092)	(1.0249)	(0.2306)	(1.0362)	(0.3766)	(0.7289)	(0.2844)
Secondary education	0.7062	3.4524	1.3219	2.0048	0.1217***	14.8250***	1.6725
	(0.2754)	(1.1667)	(0.2999)	(1.2439)	(0.7657)	(0.7600)	(0.3465)
High banana income	1.1534	0.4595*	1.1730	0.6348	0.2988**	0.7457	1.0508
	(0.1738)	(0.4672)	(0.1818)	(0.5271)	(0.5053)	(0.2843)	(0.2324)
Low banana income	0.4802***	1.0575	0.8623	0.6698	0.8494	1.4580	1.7559*
	(0.2573)	(0.4864)	(0.2610)	(0.6503)	(0.5732)	(0.3198)	(0.3104)
Middle-aged farmers	1.5296	0.4853	1.5986	1.3350	1.4480	0.9204	0.9432
	(0.3448)	(0.6482)	(0.3807)	(0.8137)	(1.0857)	(0.4871)	(0.4281)
Older farmers	1.4349	0.6106	1.8125*	0.6418	1.8805	0.9120	0.7308
	(0.3223)	(0.5727)	(0.3580)	(0.7921)	(1.0442)	(0.4495)	(0.4010)
Constant	0.8726	0.0154***	0.1770***	0.0015***	0.1854	0.0101***	0.2164***
	(0.3833)	(1.1770)	(0.4290)	(1.5910)	(1.0885)	(0.8747)	(0.4917)

Note: Variables with "*", "**", and "***" are significant at 1%, 5% and 10% significance levels.

3.3.2.3 Perceived usefulness of mobile phones in agriculture

Results in Table 3.7 are responses to the question "To what extent do farmers currently find mobile phone services useful for their work as banana farmers?" The main factor influencing the perceived usefulness of mobile phones in agriculture was education level. Both primary and secondary education are more likely to recognize the usefulness of mobile phones, compared to farmers without education.

Table 3.7: Odds ratios and standard error (in parentheses) for the ordinal logistic regression model for farmers' perception of usefulness of mobile phones in agriculture

Variable category	Variable name	Odds ratios and S.E.
Outcome	ICT perceived as somewhat un-useful (Order 2)	12.9778*** (0.3121)
	Neutral (Order 3)	1.6548** (0.2558)
	ICT perceived as somewhat useful (Order 4)	0.8896 (0.2559)
	ICT perceived as very useful (Order 5)	0.0606*** (0.2786)
Predictor	Cooking banana farmers	1.0925 (0.1812)
	Livestock-based farmers	1.1988 (0.1714)
	Male farmers	0.8765 (0.1546)
	Primary education	3.1594*** (0.1928)
	Secondary education	5.5363*** (0.2668)
	High banana income	1.0116 (0.2519)
	Low banana income	0.9061 (0.1641)
	Middle-aged farmers	0.9026 (0.1682)
	Older farmers	0.7917 (0.3111)

Note: Variables with "*", "**", and "***" are significant at 1%, 5% and 10% significance levels.

3.4 Discussion

In this study, we evaluated ownership and use of mobile phones among banana farmers in Rwanda, considering farmers' heterogeneity. Specifically, we assessed how different farm types are associated with the use of mobile phones, studied barriers to the use of mobile phones, and analyzed the farmers' perceived usefulness of using digital technologies. Generally, our results confirm that farmers' heterogeneity is associated with the ownership and use of both basic and smart mobile phones among farmers. The most prominent factors associated with mobile phone usage are education, farm type, and gender. Moreover, we provided empirical evidence to support future interventions vis-à-vis the use of mobile phone-based agricultural services.

3.4.1 Hypotheses

In Section 2, we proposed a few hypotheses. Here, we evaluate them to see how these hypotheses hold based on our results.

H1: Farm types are distinct and differentiated by the use of both basic and smart mobile devices

Given the analysis results, we accept hypothesis H1. First, we found that banana farmers are heterogeneous and can be grouped mainly by their main production systems into three types: beer banana farmers, cooking banana farmers, and livestock-based farmers. Differences in banana farming systems might be partially attributed to the differences in production environment, such as soil and climate, as well as the culture of the community (Cetin et al., 2018; Nsabimana et al., 2008; Verdoodt & Van Ranst, 2003). Different types of farmers in contrasting farming contexts may well have diverging preferences in the adoption of innovations (Blazy et al., 2009).

Second, we found that different types of banana farmers differed in their ownership and use of mobile phones. Cooking banana farmers were more likely to own and use both basic and smartphones, livestock-based farmers were more likely to own and use basic phones, and beer banana farmers were less likely to own and use mobile phones. Our results show that the cooking banana farm type is more ready to use phone-based digital tools for agronomic advice than the rest of the banana farm groups (McCampbell et al., 2021).

Given low levels of education among our surveyed farmers, it makes sense that basic phones, which require minimal literacy skills, are significantly preferred. Requiring only simple skills to make calls or read short messages, basic phones enable farmers to connect with extension agents. At the same time, basic phones might disable another group due to limited literacy skills or income-related factors; thus, we agree that farm types are distinguishable based on ownership and use of basic mobile phones.

We distinguished ownership of basic and smart mobile phones with the argument that the need for communication, which is universal according to Maslow's hierarchy of needs, creates an equal prospect to own and use basic phones. Therefore, limited literacy skills in our sample would have rendered our high-income sample not significantly likely to own and use smartphones. Even though Kang & Jung (2014) argued that the need for safety and self-actualization predicted the propensity to own and use smartphones in the US and Korea, these prepositions could not be generalized to low-literacy farmers in developing countries.

H2a: Farmers with higher income and more education are likely to own and use mobile phones

We assumed that income from bananas could influence ownership and use of mobile phones. However, our results did not support this hypothesis. The possible reason for this might be that we only used income categorically, unlike other studies that found a positive income effect. Furthermore, we did not use all household income from all possible sources (other agricultural activities, off-farm income, remittances, etc.). It is important to note that agriculture in Rwanda is dominantly subsistence, and most of our respondents had zero income. Nevertheless, although our regression model does not show a significant association of income from bananas with ownership and use of mobile phones, the group with the highest proportion (31%) of farmers in the high-income category (cooking banana farmers) had a higher likelihood of owning and using both basic and smart mobile phones.

Our results contradict most existing studies, which showed that owning a mobile phone is positively associated with income (Hoang, 2020; Katz & Aspden, 1998; Pierpaoli et al., 2013; Sekabira & Qaim, 2017; Tadesse & Bahiigwa, 2015). However, our results partially agree with Forenbacher et al. (2019), who did not find significant evidence that income is associated with mobile phone ownership.

As for the hypothesis on the education level, our results are in line with most previous findings (Folitse et al., 2019; Forenbacher et al., 2019; Michels et al., 2020). We confirmed that farmers with higher education were more likely to own and use mobile phones, although most farmers we interviewed had relatively low levels of education. The use of mobile phones requires some literacy basics, such as being able to read and write to make calls or read text messages. In our sample, we observed that nearly 83% of farmers had not gone beyond primary school, suggesting that the sample was very low on literacy basics. Furthermore, it is important to note that mobile phones currently do not support Kinyarwanda, a Rwandan local language, except for a few applications. Therefore, basic literacy skills were necessary to use mobile phones, hence supporting H2a.

H2b: Younger farmers are more likely to own and use mobile phones

Our results show that older farmers were more likely to own and use basic mobile phones compared to younger farmers, which contradicts existing studies (e.g., Michels et al. (2020). This is surprising even though younger farmers were less likely to be restricted by technical know-how in using mobile phones (as shown in Table 6). The reason might be that younger farmers, especially those with higher education levels, are less willing to engage in agriculture and more likely to migrate to cities and take off-farm jobs. Hence, fewer highly educated young farmers are engaged in banana farming. This is clearly illustrated in Figure 4a—all three types of banana farms involved less than 7% of young farmers. This sampling bias may have distorted the estimation.

3.4.2 Challenges of using mobile phone-based agricultural services and the relevance of mobile phones in agriculture

The main barriers banana farmers experienced in using mobile phone-based agricultural services are interrelated, to some extent—for example, the lack of awareness of the existence of mobile phone-based agricultural services, and the limited availability of such ICT-based services. However, we believe that farmers who indicated that they were restricted by the limited availability of ICT services had a certain level of interest in looking for these services. The same applies to farmers who indicated that they were restricted by technical know-how and those who were limited by low levels of ICT literacy. We argue that those who were limited by the level of ICT literacy seemed to be aware of a certain level of ICT literacy that they did not have. Therefore, most of the barriers farmers faced were largely related to low levels of education. Specifically, beer banana farmers, older farmers, uneducated farmers, and subsistence farmers were disadvantaged concerning the use of mobile phone-based agricultural services. Moreover, uneducated farmers were more likely to perceive the use of mobile phones in agriculture as irrelevant. Network failure, which was identified by Folitse et al. (2019) as the major constraint to the use of mobile phones in Ghana, was not such an important factor because the mobile phone network in Rwanda is relatively reliable.

3.4.3 Policy implications

Our findings provide reliable empirical evidence to effectively guide and customize agricultural policy formulation with regards to using ICT-based services in agriculture. Specifically, we provide evidence supporting mobile phone-based service interventions for future agricultural digitalization. Farm-type categories should be used in tailoring the most fit interventions, thus effectively moving away from the one-size-fits-all extension model that has been criticized for hampering the adoption of innovations (Coe et al., 2016; Hammond et al., 2017). Our results suggest that raising the level of education is key to overcoming most barriers that banana farmers face with regards to using mobile phone-based agricultural services. Nevertheless, the lack of awareness of the existence of such ICT services points to the need for wider public sensitization to these services. Furthermore, in line with making these services more customizable to enhance adoption, we suggest that agricultural-based mobile applications should have the option of being used in a local language, which enable use by those with low literacy skills.

Another key to successful agricultural digitalization is youth involvement. Our results show that older farmers were more likely to be limited by a lack of technical know-how, which would not be the case for younger farmers. Furthermore, the young generation in Rwanda has been benefiting from a low-cost education program since 2010. Enticing and integrating young people in agriculture from an early age would be a strategic way to bridge the education–skills gap observed among farmers. Strategies that facilitate easy access to smartphones for young farmers should be designed and put in place. Perhaps older farmers would even easily acquire digital skills from their younger colleagues.

3.5 Conclusion

By analyzing factors associated with owning and using mobile phones among banana farmers, we contribute to understanding the tendency for the use of mobile phones among rural smallholder farmers that dominate the agricultural sector in developing countries. To do so, first, we identified three distinct types of banana farmers: beer banana farm type, cooking banana farm type, and livestock-based farm type. Second, we demonstrated that identified banana farm types are distinguishable by how farmers used mobile phones as related to agriculture. Owning and using mobile phones was associated with farm type and several farmer characteristics.

The results confirmed the hypothesis that farm types are distinct and differentiated by the use of mobile devices, including basic and smartphones. First, we found that banana growers are heterogeneous and distinguished by the main focus of their respective production systems: beer banana farmers, cooking banana farmers, and livestock-based farmers. Second, further analysis showed that cooking banana farmers were more likely to own and use both basic and smartphones, livestock-based farmers were more likely to own and use basic phones, and beer banana farmers were less likely to own and use mobile phones. Our regression model showed no significant association between income from bananas and ownership and use of mobile phones; however, the group with the highest proportion (31%) of farmers in the high-income category (cooking banana farmers) had a higher likelihood of owning and use both basic and smart mobile phones. Results confirmed that farmers with higher education were more likely to own and use mobile devices. Younger farmers were also more likely to own and use mobile phones. We found that age was associated with ownership and use of mobile devices; however, no significant indication was found that younger farmers had the propensity to own and use smartphones.

Furthermore, gender and education level were significantly associated with the perceived usefulness of mobile phones in agriculture. Challenges that inhibited the use of mobile phones were mostly related to low levels of farmers' education. With the results of this study, we provide strategically important insights for policy and practices concerning digital agriculture, especially with regards to understanding farmers' heterogeneity and use of mobile phones in agriculture. Hence, our results provide reliable empirical evidence upon which future interventions targeting the use of mobile phones to support agricultural systems could effectively be based. Moreover, inferences can be made with regards to other cropping systems that are similar in context to the systems we studied.

4. Using farmer household typologies to understand Banana Xanthomonas Wilt management in Rwanda

Abstract

The objective of this paper is to evaluate how different types of farmers adopt prevention and control measures for Banana Xanthomonas Wilt (BXW). A structured questionnaire was used to collect household information from banana farmers (n = 690) in eight districts across Rwanda, distinguished by their representation of the major agroecological zones. Using principal component analysis (PCA) and hierarchical cluster analysis (HCA), we identified three types of banana farmers: (i) beer-banana farmers (39.1%), (ii) livestock-based farmers (31.7%), and (iii) cooking-banana farmers (29.1%). The identified banana growers' typologies are distinct and differentiated by their respective main farming objectives in the banana production system, thus having diverging behaviors regarding the adoption of BXW management practices. We observed that cooking-banana farmers are more concerned with BXW prevention than control, the opposite of what happens with beer-banana farmers. Livestock-based farmers, on the other hand, focus more on livestock production, possibly explaining their accrual of lower income from bananas. Beer-banana farmers have significantly less information on prevention; however, they follow the officially recommended CMU method. Generally, farmers' awareness of a particular control method or practice highly indicates that they will likely adopt such an approach. We conclude that recognition of the farm types and likely behavior of the farmers is key to purposefully tailoring agricultural development interventions toward supporting the adoption of BXW management practices.

Keywords: Agricultural Innovation Systems; farm typology; Crop disease management; Principal component analysis

4.1 Introduction

Farm diversity and heterogeneous characteristics are likely to induce differing behaviors in terms of crop management (Du et al., 2017), thus bringing diverse incentives that can favor the adoption of innovative and improved practices (Ruben & Pender, 2004). The question of farmers' adoption of certain innovations and non-adoption of others has been an important concern in agricultural innovation for decades (Mottaleb, 2018; Tey & Brindal, 2012). A popular understanding of the transfer of technology is that science develops agricultural innovation, agricultural extension providers deliver that innovation to farmers, and farmers integrate or use it in their farming systems (Garb & Friedlander, 2014; Van den Ban, 1998). Underlying the technology transfer approach is Rogers' classic diffusion of innovations theory Rogers (1962), which describes the meaning, reason, and level of uptake of a new idea transferred to intended end users. Researchers such as Senyolo et al. (2018) explored the characteristics of innovation, including its relative advantages and its fit with the existing social values and practices as one of the determinants of innovation adoption. It implicitly shows that the use of innovation is highly dependent on whether the innovation is perceived as useful and desirable for the farmer, which depends on several agroecological, sociocultural, economic, and institutional factors.

The theory of the diffusion of innovations is strongly associated with the linear top-down model of innovation, in which new academic agricultural research is thought to be optimal for agricultural practices that subsequently need to be spread by state-sponsored extension workers to farmers. Over the years, this linear model has been criticized for its overly simplistic view of the innovation process, its pro-innovation bias, and its view of farmers as passive recipients of knowledge (Leeuwis & Van den Ban, 2004). In contrast to the top-down linear innovation model, a more bottom-up process has come to the fore. This model is based on processes of joint or social learning in which different actors exchange views, examine their assumptions, and learn from each other to generate novel solutions (Pahl-Wostl et al., 2007; Röling & Wagemakers, 1998). Schut et al. (2014) and Wigboldus et al. (2016) advocated a systematic approach by taking into account the complexity of agricultural systems that interact with socio-economic, institutional, and environmental factors. In addition, the system approach involves multidisciplinary teams and gives credit to farmer participation (Flora, 2018) as a key to the successful scaling of innovations.

However, the problem with these participatory forms of innovation is that they often lead to unique solutions that are difficult to apply in other contexts and at other times (Beers et al., 2014; Hermans et al., 2011; Van de Kerkhof & Wieczorek, 2005). This means that farmers tend to be treated as a uniform monolithic group without much differentiation between farmers being made (Coe et al., 2016; Hammond et al., 2017). Researchers such as Makate et al. (2018) recommended that to increase adoption, policy makers should consider farmers' heterogeneity. The question here is how the lessons from individual, successful groups or projects can be generalized and applied to a wider public (Hermans et al., 2016; Millar & Connell, 2010; Sartas et al., 2020). Although farmers and farmers' knowledge receive a lot of attention in the initial phases of innovation development, in later phases of the scaling process this attention often disappears, and researchers focus more on the characteristics of the agricultural innovation system to derive scaling strategies. This agricultural innovation-system perspective provides an analytical framework to study the technological change in agriculture as a process of actions and interactions among a diverse set of actors engaged in generating, exchanging, and using knowledge (Hall et al., 2003; Klerkx et al., 2012).

Understanding farmers' diversity can provide the needed basis to address unique needs per farmer. However, this could be logistically impractical and cost-prohibitive and sets unrealistic expectations (Köbrich et al., 2003). Farm typology development, which groups farmers into types or clusters with common characteristics, is a practical way to account for the diversity and heterogeneity of farms (Daxini et al., 2019; Hammond et al., 2017; Köbrich et al., 2003). With this, we advocate that different types of farmers adopt different crop management practices. Understanding the linkage between farm typology and heterogeneous behaviors is critical for agricultural extension systems and the design of targeted intervention measurements to enhance sustainable agricultural development (Kamau et al., 2018). The most common conclusion of typology analysis is that it is a useful tool for tailoring future interventions and policies (Hammond et al., 2017), a decisive factor to adopt innovation (Daskalopoulou & Petrou, 2002), and a basis for ex-ante interventions (Lopez-Ridaura et al., 2018). It explains farmers' intentions to respond to a number of scenarios (Daxini et al., 2019; Nainggolan et al., 2013). Although typology analysis has been used for other purposes such as exploring the impact of innovative agricultural practices (Lopez-Ridaura et al., 2018), in this paper, we stand on the side that a farm type is an explaining factor in the diversity of crop management behaviors.

This paper is based on the case of BXW to understand the implications of farm typologies for innovation adoption behaviors. The management of banana pests and disease in Rwanda is a good case for studying farm typologies concerning innovation adoption. This is rational by the fact that banana production covers a multidimensional production system, and the crop is grown in almost all agroecological areas, in addition to covering different categories of farmers in terms of a socio-economic point of view. We focus specifically on Rwanda as a case study, considering the importance of banana for food security and the persistence of the disease despite efforts to control and prevent it. Bananas occupy a large part of arable land in Rwanda (23%) (Uwamahoro et al., 2019), are grown by 90% of the households (Nsabimana et al., 2008), and contribute significantly to the diets of farmer households (Gaidashova, 2006; Nkuba et al., 2015). Yet, the crop is threatened by BXW to the level that it has become a governmental concern. BXW is a bacterial disease caused by *Xanthomonas campestris,* and it has spread throughout East Africa, sometimes resulting in up to 100% of farm-level yield losses (McCampbell et al., 2018; Tripathi et al., 2009).

Since the manifestation of BXW, research has been conducted into how to prevent and control the disease starting from methods used for similar transmittable diseases (Jogo et al., 2011). The initial control method is the notorious CMU (McCampbell et al., 2018), the removal of the whole plant biomass of the mat where BXW is diagnosed. It is the preferred method for extension service providers in Rwanda. This method has the advantage of removing a larger portion of the inoculum of BXW (Blomme et al., 2017). Considering the rapid spread of the disease and the crop loss resulting from its infection, CMU can help hastily dealing with BXW hastily. However, this method also has serious disadvantages for the farmer who adopts it (especially concerning the collateral damage to banana trees that are not affected). The method is labor-demanding and thus costly. It is tedious and time-consuming and exposes the soil to erosion, hence resulting in potential decreasing soil fertility. A new innovative practice for BXW management has been developed, so-called SDSR, which has proven successful in pilot projects (Blomme et al., 2019). According to research and from personal discussions with expert plant pathologists, CMU can eliminate the disease if performed properly and followed by proper prevention measures (Blomme et al., 2017). The intriguing question is why, despite the attention and efforts from the government, the disease is still popping up in the same or different areas and is likely to become a long-term prevailing challenge. In this paper, we hypothesize that the low adoption rate of BXW management innovations and the lack of proper integration into the actual context of the farming system is associated with the promotion of technology as *"one size fits all*."

A few studies (Blazy et al., 2009; Blazy et al., 2010) have characterized the typologies of banana farmers; however, their findings are based on highly specialized banana farmers and are therefore not easily applicable to the context of Rwandan smallholder farming systems. Furthermore, limited knowledge exists about how the farm typology approach can be applied to understanding and leveraging the diversity of crop disease management behaviors and practices for optimal production. In this paper, we aim to investigate the relation between banana farmers' household typologies and the management of BXW disease in Rwanda. Specifically, we focus on identifying the main variables distinguishing banana growers into farm types in Rwanda and how this is associated with the adoption of innovative BXW management and prevention practices. We compare the knowledge and use of BXW prevention and control practices to understand (i) whether different types of farmers have different knowledge regarding BXW management, and (ii) whether knowing the practices can be associated with the adoption of them. This research provides new insight that will support moving beyond existing *"one-size-fits-all"* concepts for BXW control and prevention, as well as the whole banana management innovation system.

In the subsequent theoretical section, we link the traditional technology transfer approach, and especially its emphasis on farmers' characteristics, to the potential of locally developed innovations to scale to other regions. In the methodology section, we go deeper into the case of BXW in Rwanda and our approach to data gathering and processing. The results section presents the identified farmer typologies of banana farmers in Rwanda, and in the discussion section we link these farmer types to their implications for different BXW prevention and control practices.

4.1.1 Farmer heterogeneity in innovation adoption

Agriculture is one of the enterprises functioning in diverse environmental and socio-economic conditions resulting in heterogeneous farm characteristics and diversity in crop management practices (Gil et al., 2019). Because of this agricultural experience, unstable productivity still occurs despite efforts made by researchers and stakeholders through innovation development and transfer. Various studies in Sub-Saharan Africa (SSA) have put forward the high levels of variability among smallholder farmers along different dimensions such as their socio-economic conditions (Bidogeza et al., 2009; Kansiime et al., 2018; Nabahungu & Visser, 2011; Tittonell et al., 2005). These differences in context also lead to differences in perceptions and decisions (Neumann & Hermans, 2017). Ilbery (1978) stated that a farmer's decision regarding the uptake of innovations is complex and mainly influenced by the biophysical environment, financial resources, and individual attitude toward risks. Famers are also diverse in terms of economic perception where some farmers are profit maximizers, and others are utility maximizers (Bidogeza et al., 2009). Furthermore, different farm types are likely to have diverging efficiency in the use of agricultural resources (Kansiime et al., 2018).

The attempt to solve the problem of complexity in agriculture results in progress in agricultural extension with increasing consideration of farmers in the system. The technology-oriented approach between the 1950s and 1980s regarded farmers as adopters of technology, and systems-oriented approaches between the 1980s and 1990s considered farmers to be sources of information. Between the 1990s and 2000s, AKIS considered farmers experts and experimenters, whereas agricultural innovation systems (AIS) from the 2000s onwards have counted farmers as partners in innovation networks (Schut et al., 2014). Although the system approach brought attention to the context-specific in terms of sociocultural, economic, and agroecological drivers (Schut et al., 2014), there was no significant move from the *"one-size-fits-all" to "best-fit"* approach (Birner & Anderson, 2007). The one-size-fits-all approach in agricultural innovation systems is used to indicate that a technology developed by researchers and promising to improve production is scaled as if it is addressed to a single context, considering all farmers as homogeneous regardless of environmental and socio-economic differences (Tödtling & Trippl, 2005). The current widely discussed approach is termed the "tailored approach," which significantly shows consideration of farms and farmers' heterogeneity in the context of point of view (Hammond et al., 2020).

To reduce some of the inherent complexity of such a wide diversity, researchers have tried to come up with certain farmer typologies. A farm typology study can be used to classify farm households based on socio-economic characteristics to understand how they would react differently to the adoption of innovations based on their diverging priorities (Bidogeza et al., 2009; Daskalopoulou & Petrou, 2002; Hammond et al., 2017). Nevertheless, it is crucial to understand that the typology approach can be applied in a variety of fields and interpreted in different ways depending on the goal or selected distinguishing factors. According to Matus et al. (2013), typology studies differ in their focus, methodology, and types of data used. For example, there could be geographical or spatial-based typologies (Van de Steeg et al., 2010), technological-based typologies (Kamau et al., 2018), and institutional-based typologies (Karantininis & Zylbersztajn, 2007). In agricultural settings, the approach has been used with the aim of effectively scaling agricultural innovations. Thus, the majority of typology studies are socio-economic and farming-systems–based (Köbrich et al., 2003). What is common is that typology defines more or less the objective of the group and highlights the main distinguishing characteristics.

The typology approach generates a practical tool to guide the process of research and development planning (Lopez-Ridaura et al., 2018). This approach has been supported by the FAO as a tool to document the diversity of agricultural systems and to support the design of agriculture-related policies (Matus et al., 2013). In this case, typology analysis targets first the characterization of farms and farmers by grouping them into clusters with similar characteristics; thereafter, the generated typologies are used to understand what is happening in different groups. This approach has been used in research primarily to account for the heterogeneity of farm households and livelihood (Lopez-Ridaura et al., 2018), but also to understand how farm household types can inform the development and adoption of innovations. Furthermore, farm typology analysis could be a starting point in anticipating farmers' preferences in the context of agricultural innovation systems (Martin-Collado et al., 2015). The study by Hammond et al. (2017) used the farm typology approach to understand the diversity of motivation to adopt agricultural innovation; however, the author highlighted the need for variables other than farm characteristics to understand the better motivational orientation of farm types.

The most commonly used variables to understand farmers' heterogeneity are socio-economic characteristics including a farmer's status or personal attributes (gender, age, education, income, family size, etc.) (Bidogeza et al., 2009; Dossa et al., 2011), farm characteristics (land size, number of plots, soil type, farm income, labor, etc.) (Bidogeza et al., 2009; Blazy et al., 2009; Blazy et al., 2010), technologies used (input, conservation practices, etc.) (Bidogeza et al., 2009; Blazy et al., 2009; Blazy et al., 2010), livestock ownership (type, number, density, etc.) (Dalgaard et al., 2006; Dossa et al., 2011; Wallenbeck et al., 2019) and behavior (perceptions, attitude, etc.) (Barnes et al., 2011; Hammond et al., 2017; Kansiime et al., 2018). Studies such as those by Nabahungu & Visser (2011) and Klapwijk et al. (2014) categorized farmers into wealth categories to understand their respective access and allocation of agricultural resources. In addition to this, Kansiime et al. (2018) showed that different farm types are likely to have diverging efficiency in the use of agricultural resources.

4.2 Materials and methods

4.2.1 Household survey data

This study used data from a household survey conducted in July and August 2018 by trained enumerators. Farmer household information was collected in eight districts (Burera, Rulindo, Gatsibo, Kayonza, Gisagara, Muhanga, Karongi, and Rubavu), which were purposively selected for their representation of the major agroecological zones as well as their representation of different types of banana producing farmers in 4 provinces in Rwanda. The questionnaire contained close-ended questions on household information on a wide range of topics. For this paper, we considered only data related to socio-economic characteristics, banana production system characteristics, extension services received and adopted practices for BXW prevention and control. These variables were used to identify factors responsible for farmers' heterogeneities and to categorize them into farm typologies, whereas variables such as BXW prevention and control practices were used to understand the behaviors of typologies' regarding decisions for preventing and controlling BXW.

The selection of districts was conducted based on expert knowledge (mainly through multiple consultations with the banana program leader at the RAB) and raw data from a countrywide rapid assessment of BXW status conducted by RAB between 2017 and 2018. District coverage of main agroecological zones is summarized in Figure 4.1, whereas the area covered by banana crops in respective districts is summarized in Table 4.1. In terms of the total area covered by bananas, Gatsibo, Kayonza have more land allocated to banana production. However, Muhanga and Karongi have a higher proportion of land allocated to bananas compared to the total cultivated area (Table 4.1). Sectors and cells were selected based on expert input from district and sector agronomists. The sampling team aimed for the selection of villages with a minimum distance of 5 km between any two villages. The selection of farmers considered the gender of household heads when selecting five farmers in each village, two of which were female. In total, 690 farmers were interviewed in 138 villages.

Table 4.1: Main characteristics of studied districts

District	Cultivated area (ha)	Total B. area (ha)	C.B. Area (ha)	B.B. Area (ha)	Prop. Banana land (%)
Burera	28100	2341	806	1317	8,3
Rulindo	25146	7835	1613	4182	31,2
Gatsibo	52860	16307	8365	5227	30,8
Kayonza	48857	15318	11540	2497	31,4
Gisagara	28867	9802	2146	6218	34,0
Muhanga	30565	13394	1760	9051	43,8
Karongi	21361	8465	797	6793	39,6
Rubavu	17153	953	683	187	5,6

Key: *B = banana, C.B. = cooking banana, B.B. = beer banana, Prop. = proportion of land allocated to banana over the total cultivated area.*

Source: *(NISR, 2017)*

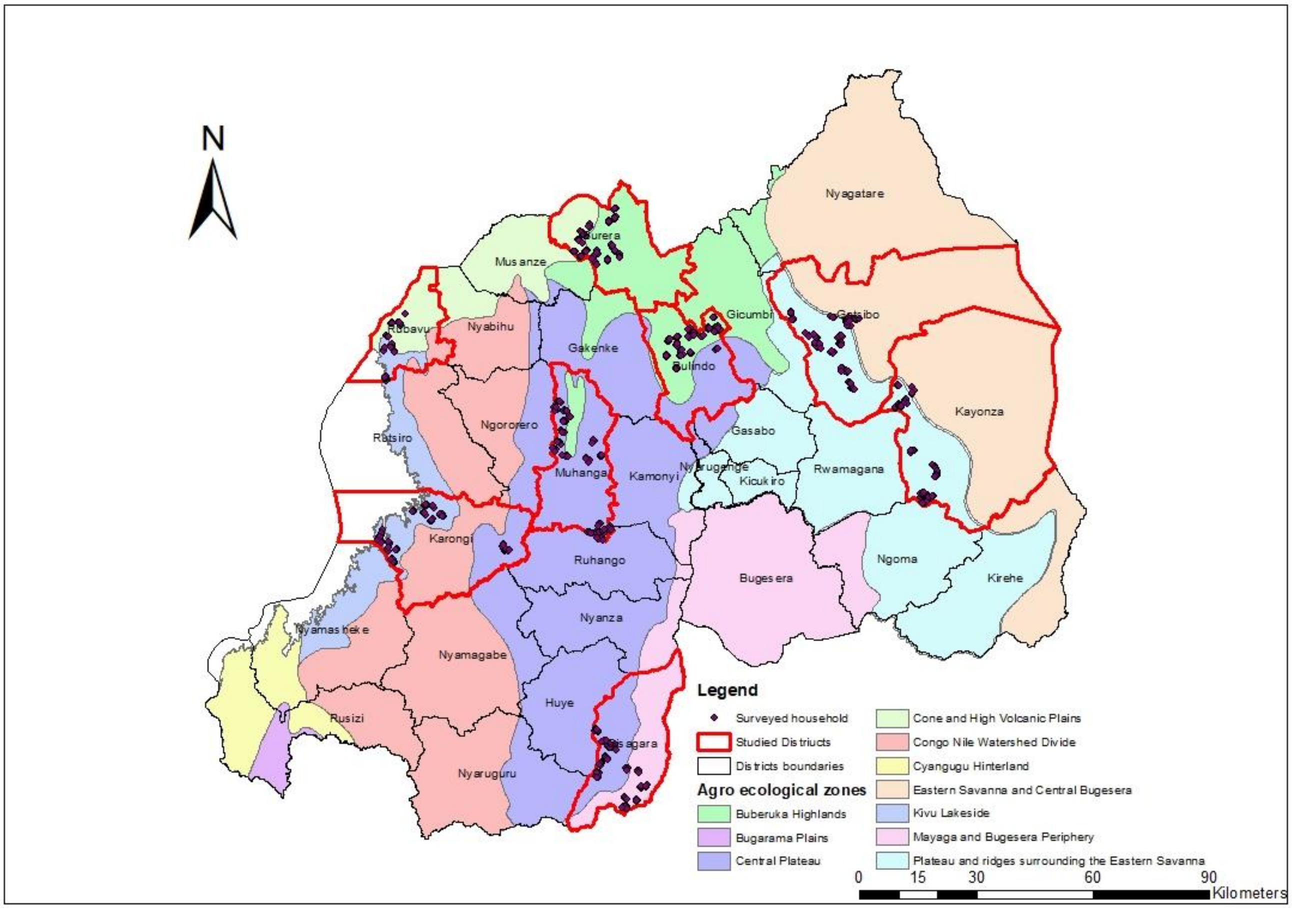

Figure 4.1: Study area map: surveyed districts and villages overlaid on agroecological zones

4.2.2 Respondents

The average age of household heads was 48 ± 14 years, and the majority of respondents had a primary level of education (67.5%). The majority of respondents were male (60%); most of them were married (83.8%), and the average household size was 5 ± 9 2 members. The median total land size owned by a household was 0.3ha, and the average tropical livestock unit was 0.94 ± 0.91. Only 30.1% of the household had off-farm income and the average income from banana was 49,790 Rwf (1 Rwf = 0.00097 Euro) per household per year. However, around 50% of them had zero income suggesting that their banana production is of subsistence. A total of 43.8% of farms growing banana intercropped them with other food crops, mainly beans, maize, sweet potatoes, cassava, and others. The majority of interviewed household farms (60%) had experienced BXW.

4.2.3 Developing farm typologies

We combined PCA and HCA to develop farm typologies. PCA was used to identify factors responsible for banana farmers' heterogeneities and to identify components for categorizing farmers into clusters (Barnes et al., 2011; Kourti, 2009). The selection of variables, which guided the questionnaire development and data collection, was primarily based on the literature review and expert judgment (Bidogeza et al., 2009). With this approach, around 60 variables were identified. The identified variables were subjected to three-step cleaning to identify those that contributed most to variance. The first step was to identify highly correlated variables; once found, one was removed, suggesting that they indicated the same thing (Alvarez et al., 2014). The second step was to identify possible outliers in the dataset by running boxplots and histograms. The observed outlier was checked to determine whether it was an outstanding value or a typing error and then dealt with accordingly. The third step was to identify variables possibly measuring the same thing by observing if they had the same sign in components. We ran PCA and observed which of the two correlated variables contributed less in the five first components. The screening of variables was systematic, that is, conducted by removing one variable at a time then running PCA again to observe changes. A total of 12 variables were identified as contributing most to the heterogeneity of banana farmers.

The 12 identified variables were subjected to PCA, the method used when variables involved are quantitative, as was the case for our retained variables. The Kaiser rule was applied to identify the principal components for further examination in cluster analysis. We purposed to retain components with eigenvalues (λ) > 1 (Jackson, 1993). Using this threshold, we retained five such components that explained 63.3% of the variance. The five components retained were subjected to HCA. This generated a dendrogram (Figure 2a) of the sequence, in which farm households were merged. The dendrogram provided a default cutting line but also allowed us to envision an alternative cutting line resulting in a different number of clusters.

4.2.4 Statistical analyses

We performed all statistical analyses using statistical packages R, version 4.0.3 (Team, 2021). Descriptive statistics including mean, standard deviation, frequency, and percentage were used to describe our respondents and developed farm types. The analysis of variance, together with the mean separation, was performed to further compare farm types by selected variables. We applied regression analysis to infer the relationship between our outcome variable (knowing vs. not knowing and used vs. did not use BXW management innovation) and our independent variable, which was farmers' typologies. Because our outcome variables were recorded as binary (dichotomously coded as 0 or 1), we applied binary logistic regression analysis (Sperandei, 2014). This type of regression is the statistical method most used to predict the probability of occurrence of a binary event by utilizing a logit function (Rutebuka et al., 2019).

The formula for binary logistic regression, as specified by (Agresti, 1996), is as follows:

$$\ln(\mathrm{P_x}/\ (1-\mathrm{P_x})) = \beta_0 + \beta_1\mathrm{X_{1i}} + \beta_2\mathrm{X_{2i}} + \cdots + \beta_\mathrm{k}\mathrm{X_{ki}}$$

where the subscript i is the i^{th} observation in the sample, and P_x is the probability of an event occurring for an observed set of variables X_i—in our case, the probability that the farmer was visited or trained, whereas $(1 - P_x)$ is the probability that the visit or the training did not occur. In addition, β_0 is the intercept term, and β_1, β_2, …, β_k are the coefficients of independent variables X_1, X_2, …, X_k.

In our logistic regression model, as presented in Tables 5 and 6, cooking-banana farmers were used as the reference group. The reference group, or reference category, consists of those individuals presenting the reference level of each variable (Sperandei, 2014). The reference group stands as a category of comparison for the other categories. In the other words, we interpreted the output by looking at the coefficients of the other groups, keeping in mind that they were obtained by comparing a particular group to the reference group.

4.3 Results

4.3.1 PCA result

Among the 62 variables that were included in PCA, 12 were identified as significant contributors to banana growers' heterogeneity (Table 4.2). These variables included both farms' and respondents' characteristics, namely the education level of the head of household, banana type grown, income from banana crop, livestock endowment, access to extension services, and household nutritional diversity. With these variables, the PCA generated 12 components, of which five components with eigenvalues greater than 1, explaining 63.3% of the variance, were retained for further analysis. The first five components explain 19.5%, 13%, 11.7%, 9.8%, and 9.3% of the variance, respectively. Table 4.2 summarizes the correlation matrix between the principal components and the 12 variables used, with their respective loadings indicating the contribution of each of the variables to the five retained components. The bolded values in Table 4.2 are those with correlation coefficients equal or above 0.4 and indicate the variable with which the component is most strongly associated. For example, the proportion of land allocated to cooking bananas is positively correlated to principal component 1, whereas the proportion of land allocated to beer bananas is negatively correlated to the same component. This indicates simply that principal component 1 is associated with cooking-banana production and dissociated with beer-banana production.

Table 4.2: Correlation matrix between principal components and variables used

Variable	Comp. 1	Comp. 2	Comp. 3	Comp. 4	Comp. 5
Nutritional diversity	0.34	-0.26	**0.57**	0.22	0.23
Number of visits by extension agent	0.13	-	0.08	**0.52**	**-0.63**
Years of education	0.16	**-0.39**	0.35	0.16	**0.60**
Tropical livestock units (TLUs)	0.15	-0.24	**0.55**	0.08	-0.19
Prop. of land for C. banana	**0.76**	**0.45**	-0.15	-	-
Prop. of C. bananas consumed	**0.52**	0.18	**-0.39**	0.32	0.33
Prop. of C. bananas sold	**0.68**	0.42	0.17	-0.21	-
Prop. of land for B. bananas	**-0.54**	**0.61**	0.24	0.31	0.18
Prop. of B. bananas consumed	-0.18	0.19	-0.25	**0.46**	0.25
Prop. of B. bananas sold	-**0.56**	**0.51**	0.39	0.11	-
Banana income	0.32	**0.44**	**0.44**	-0.30	-
People talked to	0.34	-0.10	-	**0.51**	-0.23
Eigenvalue	2.34	1.56	1.41	1.17	1.11
Cumulative % variance	19.5	32.6	44.3	54.0	63.3

Key: *Prop. = proportion, C. = cooking, B. = beer, Comp. = component*

4.3.2 Cluster analysis result

Table 4.3 describes the different clusters by variable and shows which variables are most associated with each cluster. By observing the values of the V.test and the mean in each category, we provided practical and meaningful names for the clusters.

Cluster 1, which accounts for 29.1% of farm households, is distinguished from others by having a larger proportion of beer bananas sold, land allocated to beer bananas, and beer bananas consumed. This indicates that farmers in this category are characterized by producing more beer bananas than other clusters are, thus, the practical name for them we chose is *"beer-banana farmers."* ***Cluster 2***, accounting for 31.7% of farm households, has a higher number of tropical livestock units (TLUs), higher education levels, and higher nutritional diversity as its main distinguishing features. On this basis, we named this cluster *"livestock-based banana farmers."* ***Cluster 3***, accounting for 39.1% of farm households, is dissociated from the others due to its relatively large proportion of land allocated to cooking bananas, large proportion of cooking bananas sold, and large proportion of cooking bananas consumed. This suggests that farmers belonging to this category specialize in cooking-banana production, thus, we named this group *"cooking-banana farmers."*

Table 4.3: Cluster descriptions

Typology	Variables	Mean in category	Overall mean	p-value
Type 1 (beer-banana farmers)	Prop. of B. bananas sold	0.8±0.4	0.3±0.5	***
	Prop. of land for B. bananas	0.4±0.2	0.3±0.3	***
	Prop. of B. bananas consumed	0.1±0.1	0.3±0.2	***
	Number of extension visits	1.5±1.6	0.7±0.8	*
	Tropical livestock units (TLUs)	0.8±0.9	0.7±0.9	*
	Years of education	5.6±6.1	3.1±3.3	**
	People talked to	4.8±10.6	12.3±29.4	***
	Nutritional diversity	4.7±5.1	1.8±2.0	***
	Prop. of C. bananas consumed	0.0±0.2	0.2±0.3	***
	Prop. of C. bananas sold	0.0±0.1	0.1±0.3	***
	Prop. of C. bananas consumed	0.0±0.1	0.1±0.2	***
Type 2 (livestock-based farmers)	Tropical livestock units (TLUs)	1.1±0.9	1.1±0.9	**
	Years of education	6.6±6.1	3.3±3.3	**
	Nutritional diversity	5.4±5.1	2.1±2.0	*
	Banana income*10000 (RWF)	0.2±7.0	1.2±24.5	***
	Prop. of B. bananas consumed	0.0±0.1	0.0±0.2	***
	Prop. of C. bananas consumed	0.0±0.2	0.2±0.3	***
	Prop. of C. bananas sold	0.0±0.1	0.0±0.3	***
	Prop. of land for C. bananas	0.0±0.1	0.1±0.2	***
	Prop. of land for B. bananas	0.0±0.2	0.1±0.3	***
	Prop. of B. bananas sold	0.0±0.4	0.1±0.5	***
Type 3 (cooking-banana farmers)	Prop. of land for C. bananas	0.4±0.1	0.3±0.2	***
	Prop. of C. bananas sold	0.4±0.1	0.3±0.3	***
	Prop. of C. bananas consumed	0.5±0.2	0.3±0.3	***
	Banana income*10000 (RWF)	15.4±7.0	40.9±24.5	***
	People talked to	17.6±10.6	45.6±29.4	***
	Nutritional diversity	5.5±5.1	1.9±2.0	**
	Prop. of land for C. bananas	0.1±0.2	0.2±0.3	***
	Prop. of B. bananas sold	0.2±0.4	0.4±0.5	***

Key: *Prop. = proportion, C. = cooking, B. = beer; *10000 = the value is multiplied by 10000; RWF = Rwandan franc (1 USD ~ 940 RWF); c. Values represent means (± standard deviation). Significant levels: *p < 0.1; **p < 0.05; ***p < 0.0*

4.3.3 Descriptive statistics by typology

Table 4.4 presents descriptive statistics comparing banana growers' typologies against household characteristics. Variables are grouped as (i) household characteristics, or farm and respondents' characteristics; (ii) livestock endowment, or details of number of animals by type, combined as tropical livestock units (TLUs) in PCA; and (iii) access to extension, or the interactions between farmers and extension support received through training and visits.

The beer-banana farmers had the lowest education level, lower nutritional diversity, lower income from bananas, and lower access to extension services in terms of the number of times a farmer received information or extension services, the amount of training for BXW management received by the farmer in the past two years, and the number of fellow farmers talked to or advised regarding BXW management. ***Livestock-based banana farmers*** had higher education levels, the largest households, and higher nutritional diversity, yet they had lower income from bananas. These farmers had the highest number of sheep and better access to extension services in terms of the number of extension visits in two years, people talked to, and guidance given concerning BXW management in two years. ***Cooking-banana farmers*** had higher nutrition diversity and the highest income from bananas, along with the highest number of goats. Furthermore, they had prominent access to extension services in terms of the amount of training received, number of visits by extension agents, and interaction with fellow farmers.

Table 4.4: Descriptive statistics of clusters

Variable category	Variable name	Beer BF	Livestock BF	Cooking BF
Household characteristics	Years of education	5.6 ± 3.1^{b}	6.6 ± 3.3^{a}	6.1 ± 3.6^{ab}
	Age of head of household	49.9 ± 14.8	48.7 ± 13.3	49.0 ± 12.9
	Family size	5.1 ± 2.2^{b}	5.8 ± 2.2^{a}	5.3 ± 2.1^{ab}
	Nutritional diversity	4.7 ± 1.8^{b}	5.4 ± 2.1^{a}	5.5 ± 1.9^{a}
	Banana income*10000 (RWF)	6.3 ± 14.3^{b}	0.2 ± 1.2^{c}	15.4 ± 41.0^{a}
	Total land (ha)	0.9 ± 0.2	0.9 ± 0.3	0.8 ± 0.3
Livestock endowment	Number of cows	1.0 ± 1.0	1.2 ± 1.1	1.0 ± 1.0
	Number of sheep	0.2 ± 0.7^{ab}	0.3 ± 0.9^{a}	0.1 ± 0.6^{b}
	Number of goats	0.9 ± 1.4^{b}	1.3 ± 2.1^{ab}	1.4 ± 2.1^{a}
	Number of pigs	0.3 ± 0.6	0.7 ± 3.9	0.3 ± 0.9
	Number of rabbits	0.2 ± 1.0	3.9 ± 50.7	0.2 ± 1.0
	Number of chicken	1.3 ± 2.5	2.2 ± 4.9	1.9 ± 4.9
Access to extension	Number of extension visits/2yrs	1.5 ± 0.7^{b}	1.6 ± 0.8^{a}	1.6 ± 0.9^{a}
	Number of training sessions/2yrs	1.4 ± 0.7^{b}	1.4 ± 0.7^{b}	1.6 ± 0.9^{a}
	People talked to (on BXW/2yrs)	4.8 ± 12.3^{b}	11.5 ± 23.4^{a}	17.6 ± 45.7^{a}
	People advised (on BXW/2yrs)	1.3 ± 6.5^{b}	5.0 ± 11.4^{a}	5.6 ± 18.0^{a}

Key: *Prop. = proportion, C. = cooking, B. = beer; *10000 = the value is multiplied by 10000; RWF = Rwandan franc (1 USD ~ 940 RWF). Values represent means (± standard deviation). Different superscript letters after standard deviations in a row mean statistically different (p < 0.05) according to one-way ANOVA and Tukey's HSD test. Significant levels: *p < 0.1; **p < 0.05; ***p < 0.0*

4.3.4 Banana growers' typologies of adoption behaviors

Tables 4.5 and 4.6 show BXW prevention practices (Table 4.5) and BXW control practices (Table 4.6) divided into two parts, namely, those known to the farmers and those used by the farmers. A positive coefficient indicates that the practice is more likely to be known or used by the group than by cooking-banana farmers, whereas a negative coefficient indicates that the practice is less likely to be known or used by the group or, otherwise speaking.

Beer-banana farmers had a significantly decreased likelihood of knowing about the disinfection of tools and removal of roaming animals as BXW prevention practices. Accordingly, they were less likely to practice disinfection of tools as a BXW prevention practice than were cooking-banana farmers. Furthermore, beer-banana farmers were more likely to do nothing to prevent the spread of BXW (Table 4.5). Concerning BXW control (Table 4.6), beer-banana farmers were more likely to know of practices other than CMU and single diseased-stem removal than were cooking-banana Farmers. Regarding the use of CMU and single diseased-stem removal as control methods, beer-banana farmers did not differ from cooking-banana farmers.

Livestock-based farmers did not differ significantly from cooking-banana farmers, in many cases, in their likelihood to know and use both prevention and control practices. However, like beer-banana farmers, they had an increased likelihood of doing nothing to prevent the spread of BXW in their fields. As were cooking-banana farmers, livestock-based farmers were more likely to know and practice the removal of roaming animals as a BXW prevention method. Furthermore, livestock-based farmers were more likely to use other BXW control methods than CMU and single diseased-stem removal than cooking-banana farmers.

Cooking-banana farmers, in contrast to beer-banana farmers*,* had an increased likelihood both to know and use male bud removal and disinfection of tools as BXW prevention practices. This is indicated by the fact that other groups have negative coefficients. This group of farmers also were more likely to practice the removal of roaming animals than other groups of farmers were. Concerning BXW control practices, Cooking-banana farmers were less likely to practice CMU, since other groups of farmers have positive coefficients and the p-value indicates a statistically significant difference ($p < 0.05$).

Table 4.5: Parameter estimates of binary logistic regression for the relationship between the adoption of BXW prevention innovations and banana farmers' typologies

Prevention practice		Predictor variable	Coefficient	p-value	Odds ratio
Known	Male bud removal	Cooking BF		0.002**	
		Beer BF	-0.305	0.103	0.737
		Livestock BF	0.342	0.090	1.407
		Constant	0.291	0.042*	1.337
	Disinfection of tools	Cooking BF		< 0.001***	
		Beer BF	-0.886	< 0.001***	0.412
		Livestock BF	-0.309	0.117	0.734
		Constant	-0.07	0.622	0.933
	Removal of roaming animals	Cooking BF		0.010*	
		Beer BF	-0.691	0.014*	0.501
		Livestock BF	0.093	0.717	1.098
		Constant	-1.592	< 0.001***	0.204
Used	Male bud removal	Cooking BF		< 0.001***	
		Beer BF	-0.831	< 0.001***	0.436
		Livestock BF	-0.169	0.475	0.844
		Constant	1.362	< 0.001***	3.902
	Disinfection of tools	Cooking BF		0.101	
		Beer BF	-0.377	0.047*	0.686
		Livestock BF	-0.078	0.690	0.925
		Constant	-0.17	0.231	0.844
	Removal of roaming animals	Cooking BF		0.030*	
		Beer BF	-0.475	0.131	0.622
		Livestock BF	0.304	0.289	1.355
		Constant	-1.998	< 0.001***	0.136
	Nothing	Cooking BF		0.045*	
		Beer BF	1.154	0.013*	3.171
		Livestock BF	1.006	0.038*	2.735
		Constant	-3.481	< 0.001***	0.031

Key: *BF = banana farmers, SE = standard error. Significant levels: *p < 0.1; **p < 0.05; ***p < 0.01*

Table 4.6: Parameter estimates of binary logistic regression for the relationship between the adoption of BXW control innovations and banana farmers' typologies

Control practice		Predictor variable	Coefficient	p-value	Odds ratio
Known	Complete mat uprooting	Cooking BF		0.655	
		Beer BF	-0.07	0.720	0.932
		Livestock BF	0.107	0.607	1.113
		Constant	0.649	< 0.001***	1.913
	Single diseased-stem removal	Cooking BF		0.426	
		Beer BF	-0.102	0.635	0.903
		Livestock BF	0.164	0.451	1.179
		Constant	-1.027	< 0.001***	0.358
	Other	Cooking BF		0.104	
		Beer BF	0.593	0.038*	1.81
		Livestock BF	0.283	0.363	1.327
		Constant	-2.203	< 0.001***	0.11
Used	Complete mat uprooting	Cooking BF		0.037*	
		Beer BF	0.658	0.011*	1.93
		Livestock BF	0.472	0.073	1.602
		Constant	-0.847	< 0.001***	0.429
	Single diseased-stem removal	Cooking BF		0.322	
		Beer BF	-0.401	0.157	0.67
		Livestock BF	-0.329	0.247	0.72
		Constant	-0.887	< 0.001***	0.412
	Other	Cooking BF		0.010*	
		Beer BF	0.016	0.966	1.016
		Livestock BF	0.811	0.014*	2.25
		Constant	-1.872	< 0.001***	0.154

Key: *BF = banana farmers, SE = standard error. Significant levels: *p < 0.1; **p < 0.05; ***p < 0.01*

4.4 Discussion

In this paper, we investigated the relationship between types of banana farmers and the adoption of BXW management practices. Specifically, we first defined banana farmers' typologies using PCA, which identified the main factors responsible for banana farmers' heterogeneities, and HCA, which grouped farmers into meaningful types. Then we assessed the relationship between farmer typologies, together with other control variables, and the adoption behaviors of BXW management practices. By doing so, this paper has provided empirical evidence of variables distinguishing banana farmers that could support proper tailoring of best-fit interventions regarding the management of banana production systems in Rwanda. Furthermore, this study provides empirical information about the adoption of innovations in a complex agricultural enterprise within the heterogeneous conditions of farming.

4.4.1 Variables distinguishing banana growers into different types

Understanding the variables responsible for farm heterogeneities was key to developing appropriate and useful farm types. We identified 12 variables that are mainly responsible for distinguishing banana growers in Rwanda. Variables such as the proportion of land allocated to bananas, proportion of bananas consumed, and proportion of bananas sold were expected to be correlated but they, surprisingly, are not. This suggests that there are banana farmers who use less land to produce more; intensification levels differ among farmers. Moreover, some banana farmers are subsistence producers (Karangwa et al., 2016) who have limited proportions of bananas sold, whereas others are specialized to produce more to sell than the proportion consumed. Variables that minimally affected farmers' heterogeneity included off-farm activities, banana intercropping, total land owned, experience with BXW, prevention and control methods known and used, and owning electronic devices. Variables such as total land owned and off-farm income have been used in various studies and have been identified as significant contributors to the formation of farm types (Bidogeza et al., 2009). Low variation among farmers in our case study area concerning farm size and off-farm income might lead to this minimal effect. The exact reason, however, requires a deeper detailed study of these variables in the context of banana production systems.

The banana growers' typologies we developed emphasized the main farming objective of the farmers. We believe that the main focus of a farm type is also the priority of that farm, thus, any intervention plan should take this into account. These typologies, namely, beer-banana farmers, livestock-based farmers, and cooking-banana farmers, were significant and representative of trends among banana farmers and thus were judged appropriate to define banana production systems in the country. The choice of type of banana grown is more associated with agroecological zone and the local social behavior (culture). For example, a study by Gaidashova et al. (2005) highlights that cooking-banana crops were proven to be affected by stresses such as poor soil fertility, erratic rainfall, drought, and intensive cropping systems, thus, in regions where these conditions prevail the main banana crop of choice is beer bananas. Cooking-banana farmers and livestock-based banana farmers are likely to be found in the eastern part of Rwanda, whereas beer-banana farmers are likely to be found in the southern and western parts of the country (Gaidashova et al., 2005).

4.4.2 How does farm household heterogeneity affect the adoption of BXW management innovations?

The banana growers' typologies identified are distinct and differentiated by the growers' respective main farming objectives in the banana production system, leading to diverging behaviors regarding the adoption of BXW management practices. It is important to consider that farming objective has a significant implication for the adoption and the uptake of an innovation (Morris et al., 2017). Having lower income from bananas indicates that livestock-based farmers mainly focus on livestock rather than on bananas. Therefore, they might grow bananas not necessarily as one of their sources of income but instead as an alternative source of animal (especially cattle) feed (Mutimura et al., 2015). On the other hand, cooking-banana farmers have more income from bananas, justifying their increased concern about BXW prevention in comparison to other farmers. We found that beer-banana farmers are more distinguishable from both livestock-based and cooking-banana farmers. They have significantly less information on prevention; however, this is the group of farmers who follow the officially recommended CMU method more. Nevertheless, beer-banana farmers are more likely to take no action to prevent the spread of BXW.

In addition to this, beer-banana farmers had lower education levels, poor access to extension services, and lower nutritional diversity, making them more vulnerable to malnutrition.

The significant difference in extension service access suggests that different farm types are exposed to different levels of information regarding BXW management. The study by Zamasiya et al. (2017) emphasized that better access to extension services increases farmers' chance of accessing agricultural information about innovation practices. This was evidenced by the different likelihood of knowing BXW prevention practices between beer-banana farmers and cooking-banana farmers. Therefore, we can accept the assumption that different types of farmers have different levels of knowledge regarding BXW management practices. If cooking-banana farmers, with better access to extension services, have better knowledge about CMU, the hypothesis that knowing CMU might not be connected to practicing it is possibly true, since these farmers are not likely to practice it. The fact that cooking-banana growers are likely to know and practice male bud removal and disinfection of tools, which is the opposite of what was observed in beer-banana growers, is evidence that knowing a practice provides a high probability of practicing it.

In this study, we defined access to extension services through two main sources, namely, external (amount of training received and number of visits by extension agents) and internal (number of people consulted and number of farmers advised). With this, we found that a highly significant difference between banana farmers exists in the internal (communication between farmers) than in the external (communication with extension agents). This might require an in-depth review using social network analysis to identify the structure of the farmers' underlying networks and how these networks are likely to influence crop management information sharing. This investigation would provide significant information to improve the agricultural information system by integrating informal knowledge sharing into the existing government formal extension system, as proposed by Šūmane et al. (2018). In this regard, we agree with Gava et al. (2017) who underlined that the adoption of innovation increases as knowledge networks improve.

The diverging adoption behaviors observed among the identified farm types confirms the assumption that the limited adoption of innovation is associated with using a one-size-fits-all model. However, this requires a further in-depth study to be proven with more empirical evidence. This can be done, for example, in a form of behavior modeling using farmer characteristics and observed behavior of this study as part of the model's input (Foster et al., 2014). For example, we assume that if cooking-banana farmers could be sensitized to embrace CMU, this might have resulted in positive results within this group of farmers because they practice more prevention than other groups do. However, beer-banana farmers, although they practice CMU more, might do better if they are exposed to SDSR as an alternative control method. For this, a *"what if"* scenario analysis would work. The adoption preference seems to be intrinsic to the farmers rather than to the farming system (Martin-Collado et al., 2015). The study by Berdegue & Escobar (2002) recommended that scaling of innovation should start from understanding farmers' heterogeneity through typology analysis; otherwise, it will lead to the one-size-fits-all method.

4.4.3 Policy implications

In this study, we propose considering farm heterogeneity as a step toward taking into account the complexity of agricultural systems. The identified farm typologies are a helpful tool for group-specific tailoring of intervention and scaling strategies to deal with BXW and provide insight into farm heterogeneity. We argue that policy approaches for different types of banana growers in Rwanda will differ. In this particular case, we undertook a typology analysis of banana growers not only to generate descriptive information but also to produce a valuable tool that will inform the development and adoption of innovations aimed at improving banana productivity in the smallholder farming system of Rwanda. Using the case of BXW control and prevention does not limit the use of the identified typologies to these particular activities; instead, our study demonstrates how knowledge, practices, and objectives are different between typologies, and how these affect the adoption and uptake of a particular innovation practice. It has been discussed that the limited adoption of innovation is probably associated with using a one-size-fits-all model (Coe et al., 2016; Hammond et al., 2017) which is not always relevant because farming households are heterogeneous (Kansiime et al., 2018). This knowledge could aid the design of group-specific interventions. The typologies identified highlighted the main focus and farming objectives of banana growers in Rwanda, which represent their respective existing social values and practices to be taken into consideration when scaling innovation.

During the scaling process, it may be important to approach different typologies differently to maximize the intended outcome. We observed that cooking-banana farmers are more concerned with BXW prevention than control, which makes them more willing to adopt preventive measures. The opposite applies to beer-banana farmers, who are not concerned with BXW prevention. We realized that beer-banana farmers need particular attention; they have lower income from banana crops, low nutritional diversity, and poor access to extension services. The question is why do they stick to beer bananas? The most possible reason might be their culture. Normally, the choice of banana types depends on a number of factors, including food security and dietary preference, market availability, and local social behavior (e.g. special rituals and customs in rural areas), in addition to the availability and performance of cultivars (Gaidashova et al., 2005). Beer bananas constitute the social assets for mutual support in smallholder farming systems in Rwanda, wherein most rituals and ceremonial activities, like weddings, use banana wine and/or banana juice. With the results of this study, we support the argument of Gaidashova et al. (2005) that the choice of the type of banana grown should be given special consideration in banana production policy development. The scaling of banana production innovations which ensures the integration of livestock would provide an incentive to livestock-based farmers for successful adoption. Additionally, targeting new, possibly BXW-resistant banana varieties should take into account both beer bananas and cooking bananas, to fit in with the existing social values and practices (Robinson, 2009). This was referred to as using farm types for tailored intervention and scaling strategic planning in Hammond et al. (2020). Our research provides new insight that will support moving beyond existing "one-size-fits-all" concepts for BXW control and prevention, as well as for the whole banana management innovation system.

Table 4.7 summarizes, by typology, which innovations are currently practiced for BXW prevention and control, and which extension mechanisms and capacities may need to be developed as part of a policy effort to increase effective BXW management in Rwanda. We suggest three main extension approaches, namely: (i) extension agent-based mechanism or formal government advisory services; (ii) the farmer-to-farmer or internal farmers' interaction mechanism; and (iii) the farmer promotors-based mechanism. The number of people consulted or advised on BXW management, summarized in Table 4, reflects the internal (farmer-to-farmer) extension mechanism, which is stronger among cooking-banana farmers and livestock-based farmers. On the other hand, the number of extension visits and the amount of training received reflect the formal government advisory services. The farmer promoters extension approach is similar to the farmer-to-farmer approach, except that the farmer promoters approach is the government's initiative and is structured. This model is based on two approaches, namely, FFS and FPs. An FFS facilitator mobilizes farmers in an FFS group around a field school, whereas an FP facilitator organizes farmers under a Twigire group around a demo plot (Kantengwa & Giller, 2017). Farmer promoters are volunteer community leaders who receive technical training by RAB and the local government to serve as the community-based extension system's structured extension agents in their villages. We expect that this will be used as an important tool for the future design and scaling of banana-farming related innovations to target higher adoption rates for greater development impact.

Table 4.7: Alternatives to one-size-fits-all policies for BXW management in Rwanda

Farm type	*Innovation for BXW prevention*	*Innovation for BXW control*	*Extension mechanism*	*Capacity development*
Beer BF	None	CMU	Extensions agent-based (formal mechanism), farmer promotors-based mechanism	Advanced awareness of prevention, strengthening internal networks, raising the capacity of farmer promotors
Livestock-based BF	Male bud removal, Removing of roaming animals	Other	Farmer-to-farmer (internal, informal interactions), farmer promotors-based mechanism	Awareness of SDSR as BXW control, raising the capacity of farmers' opinion leaders and farmer promotors
Cooking BF	Male bud removal, disinfection of tools	SDSR	Farmer-to-farmer (internal, informal interaction), farmer promotors-based mechanism	Awareness of prevention and CMU, raising the capacity of farmers' opinion leaders and farmer promotors

4.4.4 Limitations and future study

This study could not analyze the structure of the internal information flow, which appeared to be significant, between identified types of banana farmers. Thus, we suggest the application of ERGMs to investigate the structure of internal farmers' networks and how this is likely to contribute to existing government extension and advisory services. In addition to this, we found that knowing a practice provides a high probability of practicing it and that different types of farmers have different knowledge levels regarding BXW management practices. However, farmers do not make decisions independently, and farmers, particularly smallholder farmers, observe and learn from each other's farming practices. Individual farmer characteristics can only explain part of the heterogeneous behaviors, in our case, BXW prevention and control practices. This would provide much more insight if analyzed in the framework of a social network to understand how the network's structure influences the effectiveness of information flow. This also would provide more understanding about the tendency of farmers from the same typology to be likely to connect. It is clear that cooking-banana farmers have more knowledge and practice more BXW prevention but are not likely to use CMU as a control method. We assumed that if they practiced the CMU, followed by their usual behavior of prevention, they would see positive results; however, we couldn't prove this. In this direction, we suggest a behavior modeling study in the form of scenario analysis, using our results as model inputs.

4.5 Conclusions

In this research, we developed farmer typologies using PCA and HCA and assessed the relationship between the heterogeneity of banana farmers and the adoption of BXW management innovation in Rwanda. We found that the different banana farm types have adopted different types of BXW management practices. PCA identified the type of banana grown, the portion of the production sold and consumed, income from banana crop, livestock endowment, and access to extension services as the main variables distinguishing banana farmers' typologies. Cluster analysis grouped banana farmers in three distinct typologies, namely, (i) beer-banana farmers, who allocate large portions of land to beer bananas; (ii) livestock-based farmers, who have, besides banana production, livestock as their main enterprise; and (iii) cooking-banana farmers, who allocate large portions of land to cooking bananas. The beer-banana farmers are distinguishable from other types of farmers by their lower education level, poor nutritional diversity, and poor access to extension services in terms of training and number of visits by extension agents. In addition, they are more likely to take no action to prevent the spread of BXW, as a result of poor access to extension services. This group of farmers needs an intensive, extension agent-based approach to raise their relatively low awareness of BXW management and strengthen their relatively weak internal networks by focusing on opinion leaders. Livestock-based farmers are different from other farmers by having livestock production as their main focus, the probable reason that they have the lowest income from banana crops. Concerning BXW management, they are most likely to adopt male bud removal and removal of roaming animals as innovations for BXW prevention and to use practices other than CMU and SDSR for BXW control. They can best be reached through farmer-to-farmer "internal" extension mechanisms. Cooking-banana farmers are more concerned about BXW prevention than its control. In addition to this, because their income from bananas is higher than other types of farmers', cooking-banana farmers seem to produce bananas for both food security and income. The fact that cooking-banana farmers are more likely to know and practice male bud removal and disinfection of tools as BXW prevention practices—the opposite of what happens among beer-banana farmers—is evidence that knowing a practice provides a high probability of practicing it. We recommend that the intervention design targeting effective BXW management should be tailored to fit banana farmers' heterogeneities, presented here as banana growers' typologies.

Section IV: The importance of proximity in agricultural knowledge networks

This section is based on two papers:

The importance of proximity dimensions in agricultural knowledge and innovation systems: The case of banana disease management in Rwanda, by Michel Kabirigi, Milad Abbasiharofteh, Zhanli Sun & Frans Hermans, published in Agricultural Systems (2022), https://doi.org/10.1016/j.agsy.2022.103465.

Does the accessibility of a farmer predict the delivery of extension services? Evidence from Rwanda, by Michel Kabirigi, published in Outlook on Agriculture (2021), https://doi.org/10.1177/00307270211053876.

5. The importance of proximity dimensions in agricultural knowledge and innovation systems: The case of banana disease management in Rwanda

Abstract

Social networks play an important role in the diffusion of knowledge, and farmers draw on their personal networks to enhance their adaptive capacity to shocks. Different forms of proximity have been long recognized as important factors in knowledge and information exchanges. However, the specific roles and their interactions in agricultural knowledge and innovation systems (AKISs) are still far from clear. In this study, we investigate the underlying forces that drive tie formation within the knowledge-sharing networks of banana farmers in four different villages in Rwanda. Our study has three objectives: First, we discuss the importance of various types of proximities in AKIS research. Second, we empirically contribute on how different forms of proximity influence the way knowledge diffuses in formal and informal networks by studying a plant disease's management. Finally, we discuss our findings' relevance for targeted interventions to help rural communities transition to greater resilience. We review different proximity concepts and adapt them for use within an AKIS context. We then apply this framework to assess the proximity effects on the advice-seeking networks of banana farmers in four purposefully chosen villages in Rwanda. We used a structured questionnaire to collect social network information about the management of banana Xanthomonas wilt (BXW), from all banana growers (N = 491) in these four villages. We distinguished the informal knowledge networks among farmers from the official government extension system—the formal knowledge network. We employed exponential random-graph models to assess the determinants of the networks we observed, especially geographical, cognitive and social proximity indices. We found that geographical proximity significantly affects knowledge exchange within larger villages' informal knowledge networks; but not in smaller villages, where both cognitive and social proximities play substantial roles. We argue that farmers are socially closer in smaller communities where geographical distance does not matter, and that geographical distance only starts to matter after a certain community size threshold is reached. We provide solid empirical evidence to help plan targeted interventions toward greater resilience for rural communities. We argue that properly integrating informal social networks can result in a more effective knowledge exchange within AKISs, enhancing their resilience.

Keywords: Knowledge exchange network; proximity dimensions; BXW; Social network analysis; resilient agro-ecosystems

6. Does the accessibility of a farmer predict the delivery of extension services? Evidence from Rwanda

Abstract

To determine whether a farmer's accessibility predicts the delivery of extension services, this study used banana Xanthomonas wilt (BXW) disease-management advisory as a typical case with which to collect extension-delivery information from 690 farmers, distinguished by their respective accessibility. Cost–distance analysis was applied to define each farmer's accessibility. The results revealed that a farmer's accessibility does not predict extension delivery to that farmer in all forms of the examined extension parameters. Significant factors contributing to the delivery of extension services included BXW incidence and membership in Twigire Muhinzi groups. Given the results of this paper, I argue that the nature of the advisory and the type of farmers' networks are more predictive factors than physical proximity us. The findings of this study support the argument that the group-based extension approach is more effective; therefore, the Twigire Muhinzi initiative is recommended as a suitable model for delivering agricultural advisory services. The absence of a significant association between extension delivery and distance (accessibility) suggests that extension agents do not follow the first-reached, first-served rule but instead follow the problem solving–based approach.

Keywords: Cost-distance; Innovation systems; Agricultural extension; Twigire Muhinzi

6.1 Introduction

The importance of agriculture as a food source for the world population and the primary economic source in most sub-Saharan African countries has always compelled involved parties to invest more for its advancement by developing and transferring innovations (Traxler, 1992). Agricultural extension, dating from 1800 BC (Halim et al., 1998), plays a significant role in making new technologies visible, available, facilitating learning, and ensuring the proper use of indigenous knowledge (Anandajayasekeram, 2008). Extension agents are the main sources of knowledge supporting farmers in making informed decisions about agricultural management (Anderson & Feder, 2004; Assefa et al., 2014). This has been the formal way to disseminate appropriate information to farmers on new technologies and, thus, to foster sustainable agricultural management (Baloch & Thapa, 2018).

Despite the substantial efforts put into improving the agriculture sector, both by governments and stakeholders, agricultural production is still undergoing significant yield gaps in most East and Central African countries (Clay & King, 2019; Leitner et al., 2020). This has been attributed partly to the failure of agricultural extension services. On the other hand, studies present challenges hindering extension systems from delivering to their full potential. For examples farmers' natural and socioeconomic settings (Bernet et al., 2001), farmers' heterogeneity (Hammond et al., 2020), the complexity of agricultural systems (McCampbell et al., 2018), institutional settings (Lamprinopoulou et al., 2014), limited resources, the capacity of extension agents, and stakeholders from different backgrounds needing to cooperate (Esparcia, 2014) are listed, among others, as bottlenecks of extension services delivery.

Scientists have come up with suggestions to reorganize agricultural extension systems, both for effective adoption of improved technologies and to align with global development (Nkonya, 2009; Qamar, 2005; Sewell et al., 2017). From this viewpoint, agricultural extension has changed from a technological approach to a systemic approach through a series of approach adjustments (Wigboldus et al., 2016). Furthermore, a significant progressive shift in views of the farmer's role in the process of developing and scaling agricultural innovations has occurred, from the farmer as an adopter of technologies to the farmer as a partner and part of the innovation network (Schut et al., 2014). Many studies have been conducted to understand the bottlenecks hindering the effective delivery of extension services (Amsalu & De Graaff, 2007; Kidd et al., 2000; Olorunfemi et al., 2020).

What has escaped the attention of scientists, however, is how the distance to farmers and farmers' accessibility are likely to influence the effectiveness of extension service delivery. A farmer's location and the distance covered by the extension agent to the farmer play evident, important roles in extension service delivery (Oyegbami, 2018). Furthermore, in most cases, extension agents are limited in number and resources, which make it difficult for them to reach all farmers (Baloch & Thapa, 2018; Vouters, 2017). Although agricultural activities are strongly associated with geographical location, the spatial dimension has not yet been discussed within the Agricultural Knowledge and Information System (AKIS). Borrowing from the theoretical argument from economic geography on geographical proximity effects, extension services may be delivered first to the nearest farmers who are more accessible than others are. Another view is that the development of information and communications technologies, such as the increasing saturation of the Internet, smartphones, and social media, has brought the idea of "death of distance" as a way of abating the relevance of geographical proximity (Rietveld & Vickerman, 2004). However, much of the economic geography literature deals with Western industrial clusters or well-established agricultural clusters in Western countries (see, for example, the clusters in Ayrapetyan & Hermans (2020), and Abbasiharofteh & Dyba (2018)). I argue that the context of smallholder farmers in developing countries should be regarded as a particular case for which physical interactions are (even) more significant. For example, mobile phone ownership and use are still low among this group (Forenbacher et al., 2019), probably because it is positively associated with income, and smallholder farmers have low income (Sekabira & Qaim, 2017). In this case, the possibility of virtual communication also is limited; thus, physical interactions are still significant. Hence, it is very crucial to understand how proximity, in terms of accessibility, is likely to influence extension services delivery in the context of smallholder farming, such as in Rwanda.

To bridge this knowledge gap, I first define the factor of a farmer's accessibility using cost–distance analysis. This must take into consideration potential geographical barriers to accessibility, like topography, physical features (e.g., bodies of water or forests), the physical distance, and road networks. We used the case of banana Xanthomonas wilt (BXW) to collect information about extension visits, BXW management training, and the information source. BXW is a a fast-spreading banana disease that is easily transmitted, has no cure after infection, and can cause 100% farm-level yield losses (McCampbell et al., 2018). In Rwanda, the value of the losses due to BXW in 2015 was estimated at USD 2.95 million (Nkuba et al., 2015). The disease threatens production of bananas, the important crop for food security in the country. Bananas in Rwanda occupy a large part of the arable land (23%), is grown by 90% of households, and comprises more than 50% of Rwandans' diets (Nsabimana et al., 2008). Despite efforts by the government and stakeholders to control and prevent BXW, the disease is prevailing and is reappearing in the same areas (Geberewold, 2019). In this context, delivery of BXW management extension services is a good case because farmers desperately need assistance. The main research question of this study is whether a farmer's accessibility predicts the delivery of extension services. Regression analysis shows that the nature of the advisory and membership in farmers' groups are more relevant than a farmer's accessibility in predicting extension delivery.

The paper is structured as follows: The subsequent literature provides background about the extension system, the extension services in Rwanda, and the spatial dimension of innovation systems. The methodology goes in depth to describe the study context (including the study sites and case selection) and how the data were collected and analyzed. The Results section contains the findings, and the Discussion section links the findings with the existing theoretical arguments on the geography of innovations. I then conclude this study by highlighting its limitations and providing directions for future research.

6.2 Background literature

6.2.1 Agricultural extension overview

Agricultural extension is the process of educating farmers on how to apply scientific agricultural knowledge into practices for better agricultural productivity through training and sometimes participatory evaluation of new technologies (Swanson & Rajalahti, 2010). In developing countries like Rwanda, where agriculture is one of the main economic drivers, the agricultural extension services are essential for increasing agricultural productivity and reducing poverty (Swanson et al., 2011). Agricultural extension has existed since the advent of permanent agriculture back in 1800 BC (Halim et al., 1998). The British government first applied term "extension" to advisory services in 1914, when responsibilities for extension services were transferred to the Ministry of Agriculture. Since then, the terms "extension" and "advisory services" have been used interchangeably, but "extension" tends to express non-formal education while "advisory services" stresses technology transfer more (Swanson, 2008). The challenges that current extension services delivery faces are socio-cultural, environmental, technological, political, or institutional in nature (Peterson, 1997). For example, the social and natural environment where agriculture occurs is subjected to changes. Furthermore, agricultural production is operating on non-expanding amounts of land, yet the demand for food is increasing (Leeuwis, 2013). From a technological point of view, modernization, industrialization, and urbanization require new technologies and innovations to be developed. In this case, the extension system should be reorganized to align with global development (Qamar, 2005).

6.2.2 Agricultural extension systems in Rwanda

The government of Rwanda recognizes agriculture as a significant pillar of the country's economic development. In this respect, the country has initiated various programs for both developing agricultural technologies and conducting smart transfers of those technologies to intended stakeholders. In the framework of agricultural technology transfer, the Government of Rwanda established its national agricultural extension strategy in 2009, through the Ministry of Agriculture (MINAGRI). The guiding principles of the strategy are inclusiveness, multidisciplinary approaches and actors, a market and results orientation, and demand-driven innovations while building on other ongoing development initiatives (MINAGRI, 2009). Agricultural-related advisory is channeled into both the formal government-led and the farmer-to-farmer approaches. On one hand, the formal extension services are coordinated by the Rwanda Agriculture and Animal Resources Development Board (RAB) under the MINAGRI (MacNairn & Davis, 2018). The formal national extension structures and staff extend down to the sector level. In this study, I refer to the formal extension agents (including RAB and MINAGRI employees, district agronomists, and sector agronomists) as the government-facilitated agents.

The RAB has established the Twigire Muhinzi, a farmer-to-farmer extension model referred to as a community-based extension system (MacNairn & Davis, 2018). The model is based on two approaches, namely the farmer field school (FFS) and farmer promoters (FP) approaches, whereby an FFS facilitator mobilizes farmers in an FFS group around a field school while an FP organizes farmers under the Twigire group around a demo plot. This farmer-facilitated extension approach is coordinated by the RAB but in close collaboration with districts and sectors (Kantengwa & Giller, 2017). The FFS facilitator and the FP are identified from among farmers and equipped with different levels of training by the RAB, which is why the approach is called farmer-to-farmer extension.

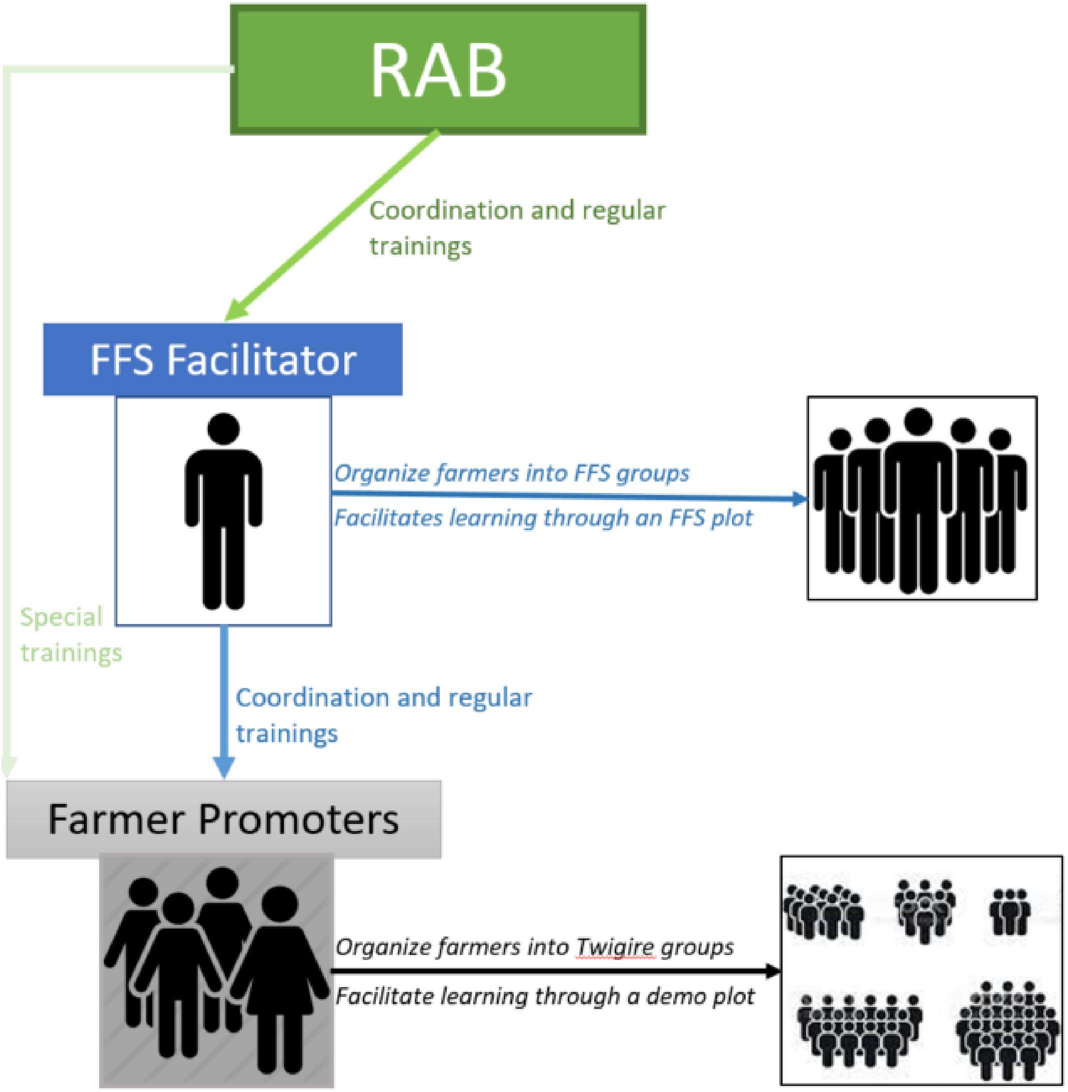

Figure 6.1: Schematic representation of Twigire Muhinzi extension model.

Note: The whole system is named the Twigire Muhinzi model and should be differentiated from "Twigire groups," which are formed at the level of farmer promoters. The term "Twigire Muhinzi groups" includes both the FFS groups and Twigire groups.

6.2.3 Geographical location and innovation system

The geography of innovations is related to evolutionary economic geography (EEG), which emerged in the 1980s to discuss the relationship between geography and technology (Boschma & Martin, 2010; Gallaud & Torre, 2005). Furthermore, the literature highlights how innovation networks are structured in space and how they evolve (Clark et al., 2018). The literature argues that understanding the geographical context of innovation is the key to properly understanding an innovation itself (Asheim & Gertler, 2005). The EEG literature discusses the spatial dimension as geographical proximity, which simply denotes closeness between individuals, in terms of geographical distance (Asheim & Gertler, 2005; Boschma, 2005). The literature distinguishes physical distance from functional distance (which takes into account the environmental arrangement). The functional distance considers road networks, forest features, water bodies, topography, and other physical barriers to determine accessibility, whereas the physical distance would determine the time needed to reach the destination. This becomes more relevant in AKIS given that extension agents are likely to be affected by both in reaching farmers. Extension agents are meant to travel to farmers to assist with the practical application of knowledge regarding innovations resulting from research. A farmer's location and the distance covered by the extension agent to the farmer play important roles in delivering extension services (Oyegbami, 2018).

6.3 Materials and methods

6.3.1 Case selection, sampling, and data collection

For this study, I used the case of advisory services provided to farmers on how to deal with BXW disease in Rwanda. This is an effective case with which to study the effectiveness of extension delivery for two reasons: i) bananas are very important to Rwanda, and ii) BXW is an aggressive, fast-spreading disease resulting in 100% yield loss (McCampbell et al., 2018). Thus, advisory on how to deal with BXW is of utmost relevance for both farmers and the government. I selected eight districts to cover the major agro-ecological zones in Rwanda and to represent different types of banana-producing farmers. At the village level, BXW incidence and the distance to extension district headquarters were classified into three levels each, resulting in nine strata that guided the sampling of villages (Figure 6.2). The strata based on BXW incidence levels were defined based on expert input from the district and sector agronomists, whereas the strata based on distance were defined using cost–distance analysis (Figure 6.3). The nine selected villages were replicated to provide 18 villages in each district, in order to provide a design for further studies of the ICT4BXW project, which will require intervention and control villages. In the Rubavu district, the number of villages was limited to 12 due to the absence of villages that matched the criteria for long distance to district headquarters. Five banana-growing households were interviewed in each village, resulting in 690 total households surveyed.

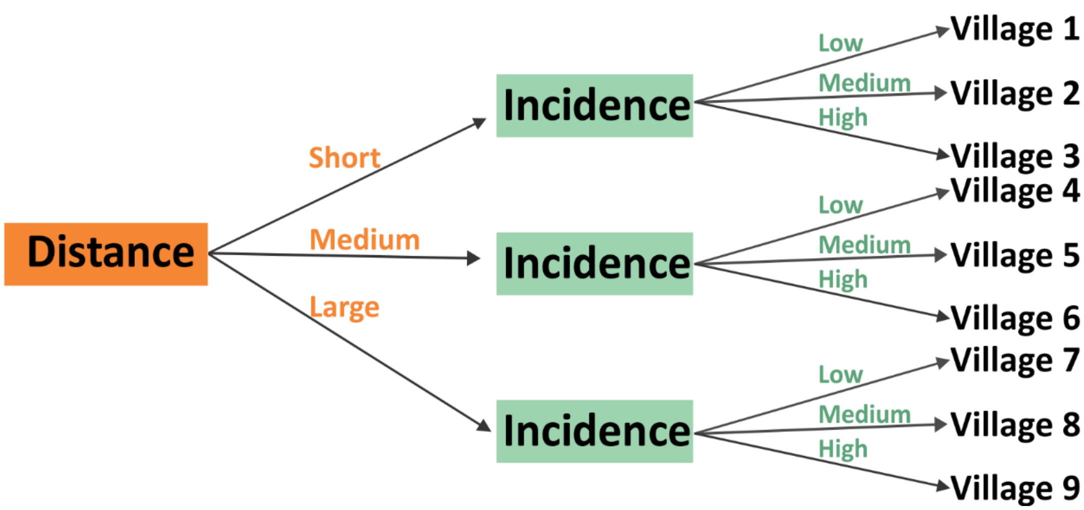

Figure 6.2: Village sampling scheme

A household survey was conducted between July and August 2018 by trained RAB technicians from the Banana Program. Data were collected using a structured questionnaire, which was developed based on the study objectives and related literature. As key outcome variables for this study, I used information collected about extension visits, trainings, and the main sources of information on how to deal with BXW. These pieces of information were recorded as responses to three main questions. The first question was, “Have you been visited by an extension agent to receive advice regarding BXW management in the last 2 years?” This was followed by the sub-question “Who visited?” The second question was, “Have you been trained on how to deal with BXW?” This was followed by the sub-question “Who trained you?” The third question was, “What is your main source of information regarding BXW management?” We categorized extension agents as i) government facilitated (RAB and MINAGRI employees, and district and sector agronomists) and ii) farmer facilitated (FFS facilitators, farmer promoters, cooperative leaders), as described in section 2. Additionally, I also collected data on other household factors like gender, age, education, and farmers’ group membership, which were used to characterize the respondents.

6.3.2 Cost–distance analysis

Each farmer’s accessibility was measured using cost distance metrics developed using ArcGIS (Greenberg et al., 2011; Mitchel, 2005). The spatial analysis tool was used to model the cost distance between the district extension office (source) and a farmer (destination) on a surface, or map grid, known as a cost raster. The optimal cost routes (referred to as the shortest path or least-cost distance) apply the distance in cost units, rather than in geographic units, based on the fundamental geographic principle of friction of distance. In this case, the farmers’ accessibility included major physical and geographical features as potential barriers to ease of access, using digital elevation maps (DEMs), land cover, water bodies, and road connections as input maps. Furthermore, the geographical location of the district extension office was used as the source, whereas the village point map was used for the destinations. A farmer’s accessibility corresponds with his or her respective village’s levels of accessibility.

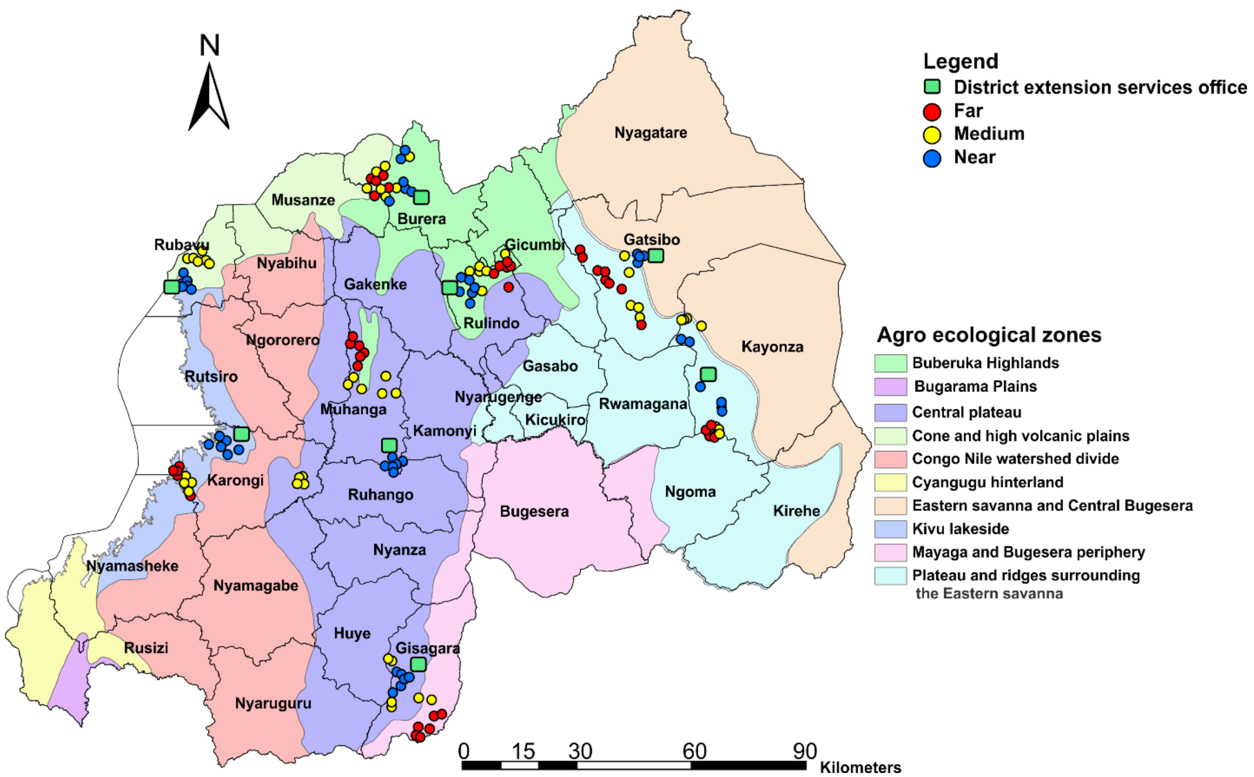

Figure 6.3: Selected villages and their respective locations vis-à-vis the location of the district extension office

6.3.3 Data analysis

The household survey data were analyzed using the statistical package R, version 4.0.3 (2020-10-10). Descriptive statistics are reported to characterize our respondents and to describe the variables used in the regression model. The nature of the data (responses) dictated the type of logistic regression model applied for this study. I used a binary logistic regression model to predict the outcome variables based on the independent variables since the data are recorded as dichotomous variables. In this case, the outcome was coded as 0 or 1 because doing so leads to the most straightforward interpretation. The formula for binary logistic regression, as specified by (Agresti, 1996), is as follows:

$$\ln(\mathrm{P_x}/(1-\mathrm{P_x})) = \beta_0 + \beta_1 \mathrm{X_{1i}} + \beta_2 \mathrm{X_{2i}} + \cdots + \beta_k \mathrm{X_{ki}}$$

where the subscript i is the i^{th} observation in the sample, and P_x is the probability of an event occurring for an observed set of variables X_i—in our case, the probability that the farmer is visited or trained, whereas $(1 - P_x)$ is the probability that the visit or the training did not occur. In addition, β_0 is the intercept term, and β_1, β_2, …, β_k are the coefficients of independent variables X_1, X_2, …, X_k.

The outcome variables used in the regression model were i) whether a farmer was visited by an extension agent to receive advice on BXW management or not (by a government- or farmer-facilitated agent), ii) if the farmer was trained or not (by a government- or farmer-facilitated agent), and iii) whether the main source of information of the farmer is either from a government-facilitated (yes or no) or farmer-facilitated (yes or no) agents.

The main independent variable for this study was the farmers' accessibility (the cost-distance). However, the data were collected from villages with contrasting levels of BXW incidence, from farmers who were or were not members of the Twigire Muhinzi group. This was an advantage because it provided additional relevant factors to compare with the farmers' accessibility.

To account for farmers who had been visited more than once, we performed analysis of variance (ANOVA) on the frequency of visits against the farmers' accessibility and the level of BXW incidence.

6.4 Results

6.4.1 Respondent characteristics

Table 6.1 shows that the farmers in the study areas were predominantly male (60.5%). Their mean age was 47.6 ± 13.7 years, and a majority of the respondents (68%) had a primary level of education. A majority of the respondents were visited and trained by government-facilitated agents. More than 60% of the farmers received BXW management information from government-facilitated agents. The mean short cost distance was 1.7 km, and the mean large distance was 5.8 km. Around 38% of the farmers were members of Twigire Muhinzi groups.

Table 6.1: Descriptive statistics (mean and standard deviation) of the variables used in logistic regression model

Name of variable (n = 690)	Description and units	Mean	Std. Deviation
General characteristics of the respondents			
Gender (male = 60.5%)	1 if male, 0 otherwise	0.6	0.49
Age	Number of years	47.6	13.7
Education level—None (18%)	1 if yes, 0 otherwise	0.18	0.38
Education level—Primary (68%)	1 if yes, 0 otherwise	0.68	0.47
Education level—Higher (15%)	1 if yes, 0 otherwise	0.15	0.48
Outcome variable			
Visited by government-facilitated agent (59%)	1 if yes, 0 otherwise	0.59	0.49
Visited by farmer-facilitated agent (45%)	1 if yes, 0 otherwise	0.45	0.5
Trained by government-facilitated agent (40%)	1 if yes, 0 otherwise	0.4	0.49
Trained by farmer-facilitated agent (34%)	1 if yes, 0 otherwise	0.34	0.47
Info from government-facilitated agents (66%)	1 if yes, 0 otherwise	0.66	0.48
Info from farmer-facilitated agents (12%)	1 if yes, 0 otherwise	0.12	0.32
Predicting variables			
Cost distance			
Large (33%)	Kilometers	5.8	1.4
Medium (33%)	Kilometers	3.6	0.5
Short (34%)	Kilometers	1.7	0.7
BXW incidence			
Low (35%)	1 if yes, 0 otherwise	0.35	0.48
Medium (35%)	1 if yes, 0 otherwise	0.35	0.48
High (30%)	1 if yes, 0 otherwise	0.3	0.46
Farmers group membership			
Member of Twigire group (29%)	1 if yes, 0 otherwise	0.17	0.37
Member of FFS group (9%)	1 if yes, 0 otherwise	0.03	0.16
No membership (62%)	1 if yes, 0 otherwise	0.51	0.5

6.4.2 Farmer accessibility and extension services delivery

Farmer accessibility had no significant relationships with being visited or receiving training. Instead, farmers with a high level of BXW incidence were more likely to be visited and trained. Furthermore, farmers who belonged to Twigire Muhinzi groups (FFS and Twigire groups) were more likely to be reached.

Table 6.2: Results from a binary logistic regression analysis on visits by extension agents and training to farmers on how to deal with BXW

Predicting variable	Visited by an extension agent		Received training on BXW management	
	Odds ratio	SE	Odds ratio	SE
Cost distance—Medium	0.819	0.1948	0.97	0.1893
Cost distance—Short	0.9801	0.1962	1.0605	0.1879
BXW incidence—High	1.7235***	0.1996	1.4998**	0.1916
BXW incidence—Medium	1.3748*	0.1875	1.2365	0.1833
Member of Twigire Muhinzi	1.7120**	0.2585	1.3543	0.2339
Member of FFS group	5.0646**	0.7637	0.8036	0.485
No membership	0.6496**	0.1811	0.9998	0.1776
Constant	1.3046	0.2103	0.6897*	0.2052

Note: Variables with *, **, and *** were significant at the 1%, 5%, and 10% significance levels, respectively.

The results from Table 6.3 present the category of the extension agents who visited or trained the farmers. Farmers with high BXW incidence and farmers who belonged to Twigire Muhinzi groups had higher probabilities of being reached by both categories of extension agents. High level of BXW incidence was the main determinant factor for a farmer to be trained by a government-facilitated extension agent.

Table 6.3: Results of a binary logistic regression analysis on the category of extension agents who visited or trained farmers

Predicting variable	Visited by government-facilitated agent		Visited by farmer-facilitated agent	
	Odds ratio	SE	Odds ratio	SE
Cost distance—Medium	0.819	0.1948	0.8915	0.195
Cost distance—Short	0.9801	0.1962	0.966	0.1933
BXW incidence—High	1.7235***	0.1996	1.4610*	0.197
BXW incidence—Medium	1.3748*	0.1875	1.0823	0.1894
Member of Twigire Muhinzi	1.7120**	0.2585	1.2936	0.2369
Member of FFS group	5.0646**	0.7637	7.9955***	0.7604
No membership	0.6496**	0.1811	0.5285***	0.1804
Constant	1.3046	0.2103	0.936	0.2081
	Trained by government-facilitated agent		**Trained by farmer-facilitated agent**	
Cost distance—Medium	0.7315	0.1955	1.0489	0.2003
Cost distance—Short	1.1496	0.1899	1.0632	0.1979
BXW incidence—High	1.5379**	0.1946	1.2284	0.2004
BXW incidence—Medium	1.0238	0.189	1.0214	0.1947
Member of Twigire Muhinzi	1.245	0.2385	1.4388	0.237
Member of FFS group	0.7075	0.5171	0.7692	0.5124
No membership	1.2227	0.1828	0.7559	0.1872
Constant	0.5368***	0.2106	0.5079***	0.2149

Note: Variables with *, **, and *** were significant at the 1%, 5%, and 10% significance levels, respectively.

6.4.3 Farmer accessibility and access to information

Table 6.4 presents the results regarding the main information source related to BXW management. The factors that increased the odds of obtaining information from both categories of extension agents were the level of BXW incidence and membership in Twigire Muhinzi farmers' groups.

Table 6.4: Result from a binary logistic regression analysis about the main source of information related to BXW management

Predicting variable	Received information from government-facilitated agents		Received information from farmer-facilitated agents	
	Odds ratio	**SE**	**Odds ratio**	**SE**
Cost distance—Medium	0.6646**	0.2019	1.8185	0.3771
Cost distance—Short	0.7079*	0.2029	1.7717	0.354
BXW incidence—High	1.1853	0.2036	3.2742***	0.3815
BXW incidence—Medium	1.1128	0.1929	2.9879***	0.3786
Member of Twigire Muhinzi	1.7440**	0.2654	19.7851***	0.4011
Member of FFS group	9.8961**	1.038	36.2657***	0.6204
No membership	0.9224	0.1843	0.6185	0.4723
Constant	2.0954***	0.2184	0.0129***	0.5088

Note: Variables with *, **, and *** were significant at the 1%, 5%, and 10% significance levels, respectively.

6.5 Discussion

The aim of this study was to assess how farmer accessibility predicts the effective delivery of extension services among banana farmers in Rwanda. We used quantitative analysis to show that the nature of the advisory and the type of farmers' network were more predictive than physical proximity was. Furthermore, the results show that the group-based extension approach was more effective; therefore, we recommend the Twigire Muhinzi initiative as a suitable model for delivering agricultural advisory services.

The findings of this study show that farmer accessibility did not predict extension delivery to farmers of all forms of extension parameters examined (extension visits, training, and source of information). In addition, farmer accessibility did not predict the frequency of visits, as presented in Figure 6.4.

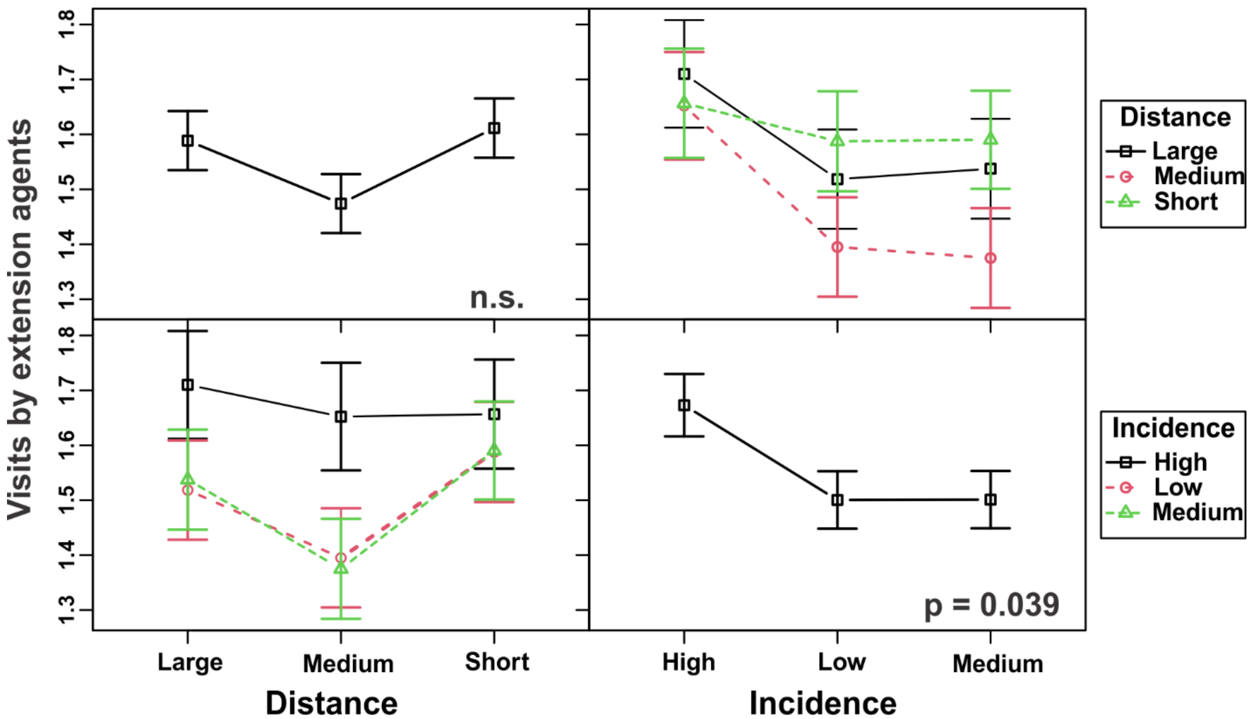

Figure 6.4: ANOVA results for visit frequency, as influenced by farmer accessibility of a farmer and BXW incidence level

The results do not support the general theoretical argument of the proximity literature suggesting that physically closer individuals are likely to interconnect and exchange information (Sykes, 1977; Ter Wal & Boschma, 2009). This proximity argument advocates that farmers who are more accessible are more likely to be visited by extension agents. The lack of association between accessibility and extension services delivery in our study can be attributed partly to the fact that infrastructures, mainly road networks, are well established, to the level at which most farmers are almost equally accessible. I will not argue much about infrastructure; however, the definition of accessibility used for this study was not based merely on the geographical (or physical) distance but also the cost (or functional) distance. The cost distance takes into consideration the natural arrangement or configuration of a location, therefore defining accessibility better.

Unsurprisingly, no proximity effect existed for farmer-facilitated extension agents because these facilitators are selected from among farmers located in the same village. Instead, both categories of extension agents are more likely to deliver extension services to farmers who have a high incidence level of BXW and those who are members of farmers' groups. Our results support the argument that the adoption of new crop-management practices is linked with the practice's role in promoting agricultural productivity (Anang et al., 2021). This argument sheds some light on the reason why extension services delivery has a significant association with the level of BXW incidence. In other words, the nature of BXW (easily and rapidly transmitted, and resulting in 100% yield losses) and the importance of banana production in Rwanda justify why farmers with high incidence of BXW receive more attention. In this case, the incidence level of the disease becomes more relevant than the farmers' proximity. Regarding the proximity argument, I support the argument of Abbasiharofteh & Broekel (2020) that proximity effects should be viewed after accounting for the context in which network actors operate. Notably, the literature argues that geographical proximity (physical distance) is neither a necessary nor a sufficient condition to interact or to share information (Boschma, 2005).

Another factor significantly affecting the delivery of extension services, as identified from the results, is membership in Twigire Muhinzi groups. Importantly, the RAB—whose mission is to develop agriculture and animal husbandry through modern methods of crop and animal production, research, agricultural extension, education, and farmer training in new technologies—is behind the implementation of the Twigire Muhinzi system (Kiptot et al., 2013; MacNairn & Davis, 2018). In this respect, the RAB equips both FFS facilitators and farmer promoters with technical knowledge. Therefore, the fact that FFS facilitators and farmer promoters are selected from farmers located in the same village facilitates access to information. The present results agree with those of Manda et al. (2020), stating that membership in a farmers' cooperative positively influences effective adoption of innovations. The logical argument here is that farmers who have regular contact with extension agents are in a better position to obtain beneficial information regarding new technology. This is in line with studies showing a higher probability of successful innovation diffusion when using the group-based extension approach (Darr & Pretzsch, 2008). In addition, the group-based extension method is an effective way of managing available resources.

6.6 Conclusion, limitations, and directions for future research

This paper was aimed at answering whether farmer accessibility can predict the delivery of extension services. We used the case of advisory services on how to deal with BXW, an infectious and fast-spreading banana disease resulting in 100% yield loss. Farmer accessibility was defined using the shortest path, or the least-cost distance, from the geographical location of the district extension office to the village where the farmers were located. The findings of this study show that farmer accessibility does not predict the delivery of all forms of extension examined (extension visits, training, and source of information) to farmers. Significant factors contributing to the delivery of extension services included the level of BXW incidence and membership in Twigire Muhinzi groups. Given the results of this paper, I argue that the nature of the advisory and the type of farmers' network were more predictive than physical proximity was. The present results support the argument that the group-based extension approach is more effective; therefore, the Twigire Muhinzi initiative is recommended as a suitable model for delivering agricultural advisory services.

Due to the nature of the data, I do not elaborate more on the social network to infer farmer attributes that are likely to increase their probability of contact with an extension agent. Therefore, I recommend a full network study to identify the effective pathways with which to deliver extension services. Caution is needed in generalizing the results to all agricultural advisory services for two reasons. First, BXW, used as the example case here, is causing devastating problems to small-scale farmers; thus, advice on how to deal with it is desperately needed. Second, the disease is too aggressive and threatens food security; therefore, both farmers and the government are alarmed. Thus, future studies should use different case studies to draw stronger conclusions.

Section V: Synthesis

7. General discussion and conclusion

This research is intended to unpack the means to reach banana farmers to provide advisory services promoting agricultural production in the smallholder farming context of Rwanda. Specifically, the research is a response to the following questions: (i) What are the main variables distinguishing banana growers in different farm types in Rwanda and how does this influence farmers' decision-making processes in adopting new practices? (ii) What role do proximity dimensions play in knowledge diffusion within formal and informal farmer advisory networks?

The results of this study provide practical information that could be useful in developing policies related to scaling innovations. The identified farm types are a helpful tool for tailoring group-specific intervention and scaling strategies to deal with BXW and provide insights into farm heterogeneity as a major concern. Identified farm types tend to focus on a specific production system, and this shapes the production objectives, which require special consideration in the scaling process. The results of this study provide important insights for the transition toward the digitalization of agriculture advisory services by showing that farm types are differentiated by the use of both basic and smart mobile phones. This research is among the first to consider the consideration of the proximity dimension as a factor to reach farmers within the AKIS framework. It provides a theoretical contribution by enriching the AKIS literature with a discussion of different forms of proximity taken from the field of EEG. In addition, it provides an empirical contribution to the study of how various forms of proximity influence how knowledge diffuses in formal and informal extension networks. This research contributes to the debate on whether proximity is still relevant for interactions in the current era of technological development by showing that in the congregated farming community, social and cognitive proximities are important, whereas in the dispersed community, the geographical proximity is important.

I will discuss these insights and the policy implications that follow from them in sections 7.2 to 7.4. I will first discuss how I responded to the research questions in section 7.1, then limitations and future outlook in section 7.2, and end with the policy recommendations in section 7.3. The last part of this section provides the overall conclusions.

7.1 Discussion of main findings

7.1.1 Main variables distinguishing banana growers into different farm types

Section III of this dissertation is focused on the research question concerning the main variables distinguishing banana growers into different farm types in Rwanda and how this influences farmers' decision-making processes in adopting new practices. Here, I discuss variables distinguishing banana growers into different farm types. An exploratory PCA with household information collected through a structured questionnaire (n=690) identified 12 variables that are mainly responsible for distinguishing banana growers in Rwanda.

Results show that variables distinguishing banana growers are related to household socioeconomic settings, the banana production system, or access to extension services. Understandably, experience with BXW as well as the knowledge of BXW prevention and control do not distinguish groups of banana farmers, which can be explained by the fast and tricky spread of the disease. Variables such as total land owned and off-farm income were expected to contribute to the formation of farm types (e.g. Bidogeza et al., 2009); however, it was not the case in this study. The exact reason for this requires a deeper, more detailed study of these variables within different contexts of production systems. In this study, the identified farm types include farmers' characteristics (individual traits) and farm characteristics (farming systems) to account for diversity in a farming community. The individual traits of a farmer build their cognitive ability, whereas the farming system shapes the farming objectives, and both are significant factors for decision-making. This approach is in line with literature that highlights farmers' attributes and farm characteristics as the main determinant factors for the adoption of innovations (Adesina & Chianu, 2002; Knowler & Bradshaw, 2007).

7.1.2 Farm types and adoption of innovations

In section III of this dissertation, I also discuss how different farm types are related to farmers' various adoption behaviors. Using hierarchical cluster analysis (HCA), three types of banana growers were identified: (i) beer-banana farmers specializing in producing so-called beer bananas, (ii) livestock-based farmers combining banana production with livestock rearing, and iii) cooking-banana farmers specializing in producing cooking bananas. Results indicated that different types of banana farmers are also likely to behave differently regarding the decision to adopt innovative practices.

This thesis is focused on how farmers belonging to different farm types behave concerning two main topics: (i) their perception and use of digital agricultural services and mobile phones and (ii) the adoption of BXW prevention and management options. Regarding the first point, the ownership of mobile phones and the type (basic or smart) of mobile phones owned is an important distinction. Results show that cooking-banana farmers are more likely to own smart mobile phones and are therefore more equipped for digital information exchange. However, this is a relatively small group, and to include the much larger group of farmers who own basic mobile devices in the digital information exchanges, it might be important to customize digital services in such a way that they also fit basic types of mobile phones. For example, chatbots, human-like conversations via text messages, could be introduced to suit basic types of mobile phones. Results from this research suggest that raising the level of education, making mobile phones (especially smart types) affordable, and providing digital services in the local language are key to advancing digital agricultural services.

Concerning farm types and the adoption of BXW management options, results show that cooking-banana farmers adopt the SDSR technique, whereas beer-banana farmers adopt the CMU technique. SDSR is a newly emerging alternative BXW control alternative with more advantages over the CMU technique, and it is mainly popular in the research community (Blomme et al., 2017). The CMU method, on the other hand, is still the official government-recommended method to deal with BXW in Rwanda (Uwamahoro et al., 2019). It could be argued that farmers who adopt SDSR are better connected to an updated source of information than the group of farmers who adopt CMU. Results of chapter 4 show that this is the case for the cooking-banana farm type. There are two possible explanations for this result. First, it can also be speculated that cooking-banana farmers are more prone to adopt newer technology than other groups of banana farmers. Not only do they adopt newer BXW techniques, but the results of chapter 3 showed that cooking-banana farmers are more likely to own smartphones, probably because they are wealthier. The second reason is that through these smartphones, they might also have better access to extension services to newer agricultural information, which would lead them to adopt the SDSR method. It is important to note that, as shown in the results, cooking-banana farmers have better access to extension services, probably because of the value of cooking-banana production in terms of food security and cash to the farmer but also the country in general.

The conclusion of this research suggests that the use of typologies to inform the scaling of development activities is a practical way to account for farm diversities and to fit well into the existing social values and practices.

7.1.3 The role of proximity dimensions in knowledge networks

In section IV, the formal and informal knowledge networks in four villages in Rwanda were investigated. Here, the following research question is investigated: What role do proximity dimensions play in knowledge diffusion within formal and informal farmer advisory networks? This question was answered through social network analysis and statistical network modeling based on a questionnaire among banana farmers.

In chapter 5, the Boschma's (2005) proximity framework was adapted for use within an AKIS context, based on a literature review. Results of this study show that proximity dimensions are relevant for interactions and the mechanism to form advice-seeking ties in informal knowledge networks. However, the effect depends largely on whether the community is dispersed or congregated. In the congregated farming community, social and cognitive proximities are important, whereas in the dispersed community, geographical proximity is important. This means that geographical proximity plays a substantial role when farmers live close together, enabling denser interactions. It can be speculated that geographical proximity plays a role, but the addition of other proximities leads to giving preference to one farmer over another for advice.

In the formal knowledge network of the AKIS, a farmer's geographical distance and accessibility do not play such an important role. This has led to investigating other possible factors predicting the delivery of advisory services by extension agents to farmers, as discussed in detail in chapter 6. The distance to farmers was translated to accessibility by applying the cost–distance technique, a GIS-based analysis to define each farmer's accessibility. Results confirmed that geographical distance does not apply when predicting a farmer's probability of being visited by an extension agent. Rather, significant factors contributing to this probability are the level of BXW incidence and membership in farmers' cooperatives and groups such as Twigire-Muhinzi. Results from chapter 6 point to the relevance of existing farmers' networks, such as farmer field schools, as a way of successfully delivering advisory services; membership in farmers' groups is one of the main predictors for a farmer to be visited by an extension agent. In this case, farmers' groups are viewed as part of the informal knowledge network.

This dissertation contributes to the debate on whether proximity is still relevant for interactions in the current era of technological development. The "death of distance" argument suggesting that the relevance of physical proximity for communication and knowledge exchange matters less was popularized in the 1990s, with the speed of ICT technology and internet progress (Rietveld & Vickerman, 2004). Studies by Sonn & Storper (2008), Abbasiharofteh & Broekel (2020), and Abramo et al. (2020) challenged the death of distance argument and supported the idea that geographical proximity is still a significant factor for social-tie formation and effective information flow. Results of this study suggest that geographical distance does not matter until a certain threshold is reached, and that below this threshold, social and cognitive proximities are relevant.

The fact that cognitive and social proximity play a role in smaller villages, where geographical proximity does not matter, points to the possibility of proximity dimensions' complementarity or substitutability. Complementarity suggests that proximities work in the same direction, whereas substitutability could be an indication that proximity compensates for the lack of another one. This study, based on the presented results, lacks convincing arguments to confirm either complementarity or substitutability of proximity dimensions. This would have required a different setup of the ERGM model and its controls. Indeed, the complementarity and substitution effects of proximity dimensions are an ongoing scholarly debate. Anecdotally, two farmers have random encounters due to geographical proximity and exchange knowledge about their activities; this interaction helps them bridge cognitive gaps (Ter Wal & Boschma, 2011). While this has been long-standing wisdom, empirical studies of the joint effects of proximities provide mixed results. For instance, Balland & Rigby (2017) showed that both geographical and cognitive proximity facilitate inventive activities in the US (i.e., complementarity), whereas Ponds et al. (2007) showed that one proximity can compensate for the lack of another one in creating collaborative ties in a co-authorship network. van der Wouden & Rigby (2019) similarly provided evidence for substitution effects (i.e., social proximity substitutes the one of spatial proximity). Recently, extant literature on economic complexity has suggested that in a knowledge exchange, the complexity of knowledge pieces determines whether proximity dimensions complement or substitute one another (Balland et al., 2022).

7.1.4 The informal vs formal knowledge network

In this thesis, the term "informal knowledge network" is used to describe knowledge exchange through farmers' interactions among themselves. The term "formal knowledge network" describes the links between government-established advisory services and farmers as an officially recognized way of transmitting knowledge from research to farmers. In the case of this study, the social network analysis showed that the informal knowledge network is important regarding BXW management advice.

The formal AKIS networks show a high number of isolates: nodes within the network without any links and that are not reached by the formal extension services. In three villages, this proportion is around one-third of the interviewed farmers, and in the village of Rusera, this proportion is even higher: two-thirds of the respondents are not connected to the formal AKIS to gain knowledge about BXW. This is understandable because extension agents are usually limited in numbers and resources. However, this indicates a potential knowledge gap amongst farmers in the process of innovation diffusion. The failure of extension agents to reach all farmers could be a possible explanation for the limitations in agricultural extension delivery and the low adoption of innovation practices. Although previous studies have recorded the tremendous work by official extension systems in improving agricultural productivity, especially in developing countries (Anderson & Feder, 2007), some scholars still insist on the need to reorganize the system (Qamar, 2005).

On the other hand, the informal knowledge network among farmers themselves is more densely connected than the formal government extension system. Further, the informal knowledge networks in all study villages are highly centralized, with an important advisory role for a few well-connected persons within each village. Persons who occupy the central position in the informal knowledge networks are so-called farmer promoters or those who are part of the village leadership in one way or another. It appears that village leaders are far more influential (more connected) in BXW advice-giving than trained farmer promoters. These results suggest that the central position of nodes within the local village advice networks is not always a result of their superior knowledge of BXW management, but more a result of these people's social status.

With the results of this thesis, it can be speculated that the potential way to optimize the formal AKIS is to link the formal knowledge network more effectively with the informal knowledge network. The consideration of informal knowledge networks, in addition to bridging the knowledge gap, would be a strategic approach to strengthening the participatory approach, facilitating demand-driven extension, making use of indigenous knowledge, and facilitating farmers' participation in research activities in the form of data collection (Beza et al., 2018; Šūmane et al., 2018).

This leads to the discussion on how to integrate the informal and the formal knowledge network successfully to optimize knowledge transmission or, formulated slightly differently, how the "secondary reach" or the formal extension network can be broadened (Danielsen et al., 2020). Two complementary ways can be suggested based on this research. The first suggestion is to use farmers who occupy the central position in the informal knowledge network as potential links to the formal knowledge network. In this case, central farmers in the informal knowledge network occupy a brokerage position in the bigger knowledge network. Social network literature emphasizes the significance of individuals and organizations' positions in an advice-seeking network, whereby embeddedness in a clique positively correlates with social trust, learning, and knowledge exchange, and a higher degree of brokerage is associated with access to sources of novelty and non-redundant information (Nedkovski & Guerci, 2021). Concerning information flow as affected by network structure, informal social networks are considerably better compared to the formal AKIS for distributing BXW management knowledge. The fact that the informal knowledge networks are densely connected indicates the higher likelihood of effective information exchange between individuals (Bourne et al., 2017).

The second suggestion is the use of ICTs to support communication-intermediation roles. The importance of geographical proximity in larger villages points to a potential role for digital solutions to facilitate knowledge exchange. Digitalization of agricultural advisory services is a hot topic in the current scientific debate, and more so as the COVID-19 pandemic has enforced limited physical interactions (Klerkx et al., 2019b; Lionboui et al., 2022). This research shows the potential of digital solutions, provided that care is taken in designing phone-based digital services to account for the type of mobile device, heterogeneity amongst farmers, and language in which digital services are accessed. The results of this study partly respond to McCampbell et al. (2021) question as to whether farmers are ready to use phone-based digital services. Although McCampbell et al. (2021) reported limited capacity to access and use digital extension services, this study shows that there is some potential to use such services amongst banana farmers. For example, at least 70% of farmers own a phone, and more than 67% of farmers find the use of mobile-based services for BXW management somewhat or very useful.

7.2 Limitations and future outlook

We analyzed our networks in static respect without considering the effect of time. Therefore, we suggest further exploratory analysis to include the dynamic perspective. Such a temporal analysis of network changes could contribute to the unconcluded debate among scholars on whether geographical proximity only matters during the initial stage of innovation (argued by scholars such as Gullahorn (1952) and Molina-Morales et al. (2014)) or if the importance of geographical proximity does not decay with time, as Abramo et al. (2020) concluded. Such an analysis could use extended versions of ERGM that have been improved to capture time effects, such as separable temporal exponential random graph models (STERGMs); see Handcock et al. (2015) for details.

Proximities are not always well-defined, and the same variables are sometimes used to operationalize different forms of proximity. For instance, Hermans (2021) gave a couple of specific examples: "The variable co-location is used to measure geographical proximity by some authors and institutional proximity by others. Similarly, the variable measuring the years of collaboration between a pair of nodes has been used both for organizational proximity and social proximity" (Hermans, 2020 p. 20). In this dissertation, the variable of a farmer's is an example of a variable that, depending on the context, could serve as either cognitive or social proximity. In this study, age is used as a proxy for social proximity because age in Rwanda, where there is no social mobility, is a significant indicator of social status—older people occupy a higher social status. In this regard, further studies are required to understand more about multifaceted variables and to draw a sensitivity analysis showing which form of proximity is operationalized by which variables.

The time and form of data collected did not allow us to evaluate all types of proximities identified in Boschma's framework empirically, such as organizational and institutional forms of proximity. This would have required farmers belonging to different institutional contexts as well as members of different farmer cooperatives. For example, Broekel & Boschma (2012) showed that organizational and institutional proximities are more often investigated based on relations between firms in various countries and regions as well as industry–university relations. This study could not be based on such information from interviewed farmers. For a complete view of how forms of proximity influence the way knowledge diffuses in AKIS, further studies considering organizational and institutional dimensions of proximities are needed.

7.3 Policy recommendations

Another important finding from network analysis is that farmers who are part of the village leadership occupy the central position of the informal network—in some cases, even more than farmer promoters. This could be an explanation for why some farmers choose CMU over SDSR. On one hand, farmer promoters are coordinated by the RAB, the national agricultural research institute, and are more likely to access updated information on the SDSR. On the other hand, village leaders are coordinated by government leadership and are more likely to focus on the CMU, an officially recommended practice. Therefore, farmers who are more connected to village leaders might be encouraged to choose CMU over SDSR. The question is now how to deal with the village leaders' roles within the knowledge network. Village leaders are not equipped with deeper knowledge on how to deal with the disease, as farmer promoters are. Furthermore, they are also involved in many other responsibilities related to village coordination that do not allow them to keep up with the intricacies of all the kinds of farming techniques that might occur in their villages.

This issue can be approached in two ways. First, it is important to acknowledge their influence and to strengthen them with training related to BXW management, as done for farmer promoters. This could align with linking them more closely with the formal AKIS, where they can access updated information from research. The second way to approach this issue is to cut them off from knowledge networks and encourage farmers to refer to local farm promotors or agronomists for advice, which would allow these village leaders to concentrate on other activities related to village coordination.

It is important to consider and acknowledge that not all farmers are reached by official government extension agents. This is evidenced by the large share of isolates observed in the analysis of the formal AKIS network and the fact that farmers united in groups are more likely to be visited by official government extension agents. In other words, these farmers are disconnected from the formal AKIS and are somewhat isolated from the community by not joining farmers' groups, thus becoming hard to reach. It is not easy to suggest a solution to this situation when the reason is not yet clear. However, the government should be aware of the existence of such cases. The easier recommendation to make is to encourage all farmers to join farmers' groups, such as Twigire-Muhinzi. However, the reason behind the situation must be studied to allow appropriate measures to be taken.

The design of innovative interventions should not deviate much from the main focus of a farm type's specific production systems. For example, in enforcing a policy limiting roaming livestock, one of the prevention measures, one must consider that some banana farmers have livestock as a primary business and banana production as a secondary business. In this case, livestock-based farmers face a trade-off between care for livestock and BXW prevention if care for livestock implies animal roaming outside. Possibly, livestock-based farmers will lean more on livestock if bananas are a side business. Another consideration concerning typology is that to facilitate the promotion of digital agricultural services, beer-banana farmers require a certain level of special consideration. This group of farmers has difficulties owning and operating mobile devices. One of the options to mitigate this would be strategies that make mobile devices affordable to them. Furthermore, awareness creation through sensitization and technical support on how to navigate digitalized services could help these farmers.

Involving the young generation in the farming community would be a solution to many problems. For example, major barriers to the use of mobile phone-based advisory services are more or less related to the level of education and ICT literacy. The young generation, besides being interested in technology, is benefiting from twelve years of a low-cost education program in Rwanda that was implemented in 2010. This program has resulted in a young generation that is better educated than many older farmers. However, involving the young generation in the farming community would require strategies that make farming more attractive—for example, by modernizing agriculture through the introduction of smart farming, mechanization, and promoting business-oriented agriculture. Another way to interest youth might be agricultural-related training tailored in such a way that it improves prospects of youth participation, as recommended by Simões & do Rio (2020).

Another important point to consider is women's empowerment to participate in both kinds of networks (formal and informal). The international development community is increasingly acknowledging that gender equality and women's empowerment are key to = economic and social development objectives, including nutrition, education, food security, and health (Quisumbing et al., 2022). The reason for emphasizing women's empowerment is that some cultures, particularly in developing countries, favor men over women in one way or another. In this study, it was noticed that women play a marginal role in the informal advice networks; men do not ask for advice from women, and advisory linkages among women themselves are generally absent. Farmer promoters and village leadership positions are occupied dominantly by men. In this respect, it is very important to establish strategies that facilitate women's selection as farmer promoters.

7.4 Overall conclusions

This dissertation is focused on the diffusion and the adoption of agricultural practices, particularly the importance of proximity dimensions and farm types. The main research question addressed was how to reach banana farmers to provide advice on agricultural production in the smallholder farming context of Rwanda. A multidisciplinary combination of research methodologies was used to obtain data to answer the research questions and test the hypotheses. The main conclusions are that to approach banana farmers, it is important to fit with the existing social values and practices, taking into account that this group is heterogeneous. In this case, the use of typologies to inform the scaling of development activities is a practical way to account for farm diversities and to fit well into the existing social values and practices.

Concerning proximity effects, this study shows that proximity dimensions are relevant for interactions and a factor in forming advice-seeking ties in informal knowledge networks. However, the effect depends largely on whether the community is dispersed or congregated. Furthermore, the proximity study was relevant to unpack more about what is happening in the informal knowledge networks than in the formal AKIS. The proximity concept can be used to strengthen the Twigire-Muhinzi initiative, an important driver to access information from the formal AKIS.

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2. Education

Years	Institutions and Schools	Degree and Certificate obtained
2018-2022	Martin-Luther-University Halle-Wittenberg, Halle (Saale), Germany	Candidate for Ph.D. in Agricultural Sciences (Dr. agr.)
2012-2015	Kenyatta University, Nairobi, Kenya	Masters of Sciences in Integrated Soil Fertility Management (ISFM).
2009-2010	Umutara Polytechnic (UP), Nyagatare, Rwanda	Bachelor of Science in Agriculture (Honours)
1999-2003	Higher Institute of Agriculture and Animal Husbandry (I.S.A.E), Busogo, Rwanda	Advanced diploma Agricultural Engineering.
1991-1998	Ecole Agriculture et vétérinaire de Kabutare (EAVK), Huye, Rwanda	Certificate of Secondary Education, level A2 in Agricultural.
1983-1991	Mbazi primary school, Huye, Rwanda	Primary education Certificate

3. Working Experience

Years	Position	Institution
Apr. 2018-Dec. 2022	PhD Student	Leibniz Institute of Agricultural Development in Transition Economies, Halle (Saale), Germany, Supervisor: Prof Alfons Balmann
Jul. 1011-Apr. 2018	Research Technician	Rwanda Agriculture and Animal Resources Development Board (RAB), Soil Conservation Program
Mar. 2005-Aug. 2011	Senior Technician	Institut des Sciences Agronomiques du Rwanda (ISAR), Soil and Water Management Unit
Jan. 2005-Aug. 2005	Community Facilitator	ISAR/CIAT/ATDT-Nutrition project
Nov. 2003-Dec. 2004	Focal point technician	ISAR/CIAT/ATDT project

4. Publications:

5.1. Peer reviewed papers

Kabirigi, M., Abbasiharofteh, M., Sun, Z., & Hermans, F. (2022). The importance of proximity dimensions in agricultural knowledge and innovation systems: The case of banana disease management in Rwanda. Agricultural Systems, 202, 103465.

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5.2 Conferences proceedings papers

Kabirigi, M., Sun, Z., & Hermans, F. (2021). Potential of Using ICT Tools for Crop Diseases Management among Heterogenous Farmers in Rwanda. Presented in the 61th annual conference of the GEWISOLA (German Association of Agricultural Economics), The Transformation of Agricultural and Food Systems: Challenges for Economics and Social Sciences, Berlin, Germany, September 22th – 24th, 2021

Wasige John E.., **Michel Kabirigi.,** Norman Kwikiriza., Robert Mwerera., Jane Bemigisha, Timothy Lubanga., Charles Galabuzi., Gerald Eilu., Daniel Nkondola, 2013. Planning Future Adaptation to climate change impacts on Crop yield in the upper catchment of Lake Victoria Basin. Presented during the first biennial conference on agricultural research and extension: Confronting challenges of food insecurity and poverty in the era of climate change and variability between August 21-23, 2013, Kigali Serena Hotel

Wasige John E., **Michel Kabirigi**., Norman Kwikiriza., Robert Mwerera., Jane Bemigisha, Timothy Lubanga., Charles Galabuzi., Gerald Eilu., Daniel Nkondola, 2013. Detecting long-term rainfall changes in Kagera basin to support climate change adaptastion policy. Presented during the first biennial conference on agricultural research and extension: Confronting challenges of food

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Kabiligi M., Musana B., Nabahungu N. L., Kurothe, R.S. (2009). Opportunities and constraints of rainwater harvesting for farm productivity improvement in nyagatare district, Rwanda. Paper presented in Soil Science Society of East Africa (SSSEA) conference (December 2009)

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Eidesstattliche Erklärung / *Declaration under Oath*

Ich erkläre an Eides statt, dass ich die Arbeit selbstständig und ohne fremde Hilfe verfasst, keine anderen als die von mir angegebenen Quellen und Hilfsmittel benutzt und die den benutzten Werken wörtlich oder inhaltlich entnommenen Stellen als solche kenntlich gemacht habe.
I declare under penalty of perjury that this thesis is my own work entirely and has been written without any help from other people. I used only the sources mentioned and included all the citations correctly both in word or content.

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Datum / Date	Unterschrift des Antragstellers / *Signature of the applicant*