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A Public Bad Game Method to Study Dynamics in Socio-Ecological Systems (Part II): Results of Testing Musa-Game in Rwanda and Adding Emergence and Spatiality to the Analysis

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Abstract: This article is the second in a series of two and presented findings from field-testing an experimental boardgame (Musa-game) with banana farmers in four villages in Eastern Rwanda. The conceptualization and design of the Musa-game were described in Part I. Musa-game gives insights into how farmers' individual and collective decision-making and actions regarding management of a public bad interplay with other factors and characteristics of the socio-ecological system (SES). A public bad is a non-rivalrous, non-excludable issue that causes loss of social-welfare of individuals and communities. The method contributes contextual understanding about the emergence of phenomena that arise from the interactions between human and non-human actors. Musa-game was framed to study one public bad challenge in particular: the infectious crop disease Banana Xanthomonas Wilt disease (BXW). Findings increased the knowhow about the emergence and governance of conditions that hinder or enhance the spread of infectious diseases like BXW. Analysis of qualitative and quantitative data suggested that individual farmers' actions were influenced by perceptions of risk, affecting both individual and collective disease management. Additionally, the used experimental treatments allowed us to evaluate the influence of communication on risk-governance strategies. It appears that a combination of possession of technical knowledge about the disease, opportunities to communicate about the disease, and a collective disease management strategy enables the best individual actions and collective performance.

Keywords: socio-ecological systems; Banana Xanthomonas Wilt; public bad; infectious diseases; games; learning; social dilemmas; digital communication

1. Introduction

Infectious diseases are public bads because they are (mostly) non-excludable and non-rival. Therefore, infectious diseases have the potential to harm a large number of hosts (plants, animals, and humans), and the infection of one host does not reduce the available pathogens to infect other hosts (but increases its infectious potential) [1–3]. The socio-ecological damage caused by infectious diseases is a function of the interaction between the environment, host, and pathogen [4] and can be disastrous. Human behavior is a critical factor in how these interactions enable pathogens to disseminate, evolve, and manifest as infectious diseases [5] (pp. 3–14). Therefore, collective and coordinated actions are required to manage public bad risks (risk governance) like infectious diseases.

Human decisions and sense-making about such decisions are the results of dynamically intertwined factors. Thus, those decisions are not only the result but also the cause of the emergence of different scenarios [6–9]. In this study, our main purpose was to explore how farmers' decision-making interplays with other Socio-ecological system (SES) factors and creates conditions that hinder or enhance the spread of Banana Xanthomonas Wilt (BXW) disease (our public bad problem) in Rwanda. To do so, we tested the value of integrating emergence and spatiality into the analysis by applying a dynamic socio-ecologic (DySE) game method. This method consisted of a public good game integrating both emergence and spatiality in its design by considering what 'I' do, what 'others' do, and what 'it' does (e.g., a disease vector) at a given geographical place, time, and socio-ecological condition (see also part 1 of this article series). A detailed description of how we developed the method was provided in the first article that we wrote about our work.

In this article, we limited the technical explanation of the method and conceptual thinking behind it to briefly contextualizing BXW disease using an adapted version of the SES framework [10–12]. Second, we field-tested the framed dynamic socio-ecological (DySE) game, named the Musa-game (Musa meaning banana in Kiswahili language). It is an experimental board game that captures what different (human and non-human) actors (involved in the BXW socio-ecological dynamics) do, at given places (banana farms), times (disease severity stages), and conditions (institutional management of BXW). Third, we explored the use of spatial analytical methods to understand the dynamic relationship between the multiple related socio-ecological factors, decision making, and resilience. To do so, we developed a computational program that includes both decisional and spatial dimensions to assist with analyzing the game's results (inspired by principles of neighbors, connectedness, and centrality analysis [13,14].

We situated our study in the context of a project, ICT4BXW, which aimed to use digital technologies and citizen science to contribute to the control and prevention of BXW in Rwanda and the East and Central African region. Using this project context, we focused on the variable of communication as a central factor affecting different actors' (inter)actions and emergent outcomes in a given space and time. By applying the Musa-game and the analysis tool, we explored and reflected on what field-test findings can tell us about individual and collective action in BXW management and the effects of communication on farmers' decision-making and its implications in the broader context of (digital) communication interventions in agriculture.

2. Theoretical Framework

2.1. Framework for Analyzing a Public Bad Risk: An Adaptation from SES Framework

Ostrom (2007) proposed the Socio-Ecological System framework to analyze the sustainability of socio-ecological systems [10]. The main components of the SES framework are a set of multilevel and nested subsystems: the resource system, the resource units, the governance system, and the users. Earlier [15] (PART I Galarza-Villamar et al. 2021), we adapted this framework such that it can aid analysis of a public bad risk that threatens the sustainability and resilience in a livelihood system. This adaptation was created from a risk management perspective, operationalizing a public bad risk based on the hazard characteristics and vulnerability conditions. The existing governance system was furthermore framed as the set of existing rules and norms that should prevent and control the hazardous consequences of the public bad. Figure 1 portrays the different subsystems identified in the context of BXW disease in Rwanda and the interactions within the socio-ecological system. In this article, we focused on the interaction between three sub-systems: the public bad risk context, the risk governance system, and the direct users (collective action problems) which we describe in the following sections. Given the scope of this article, we referred to Appendix A and additionally to Ostrom (2007) and Part I of our study for details about the original SES framework and our adapted version to explore public bad risks.

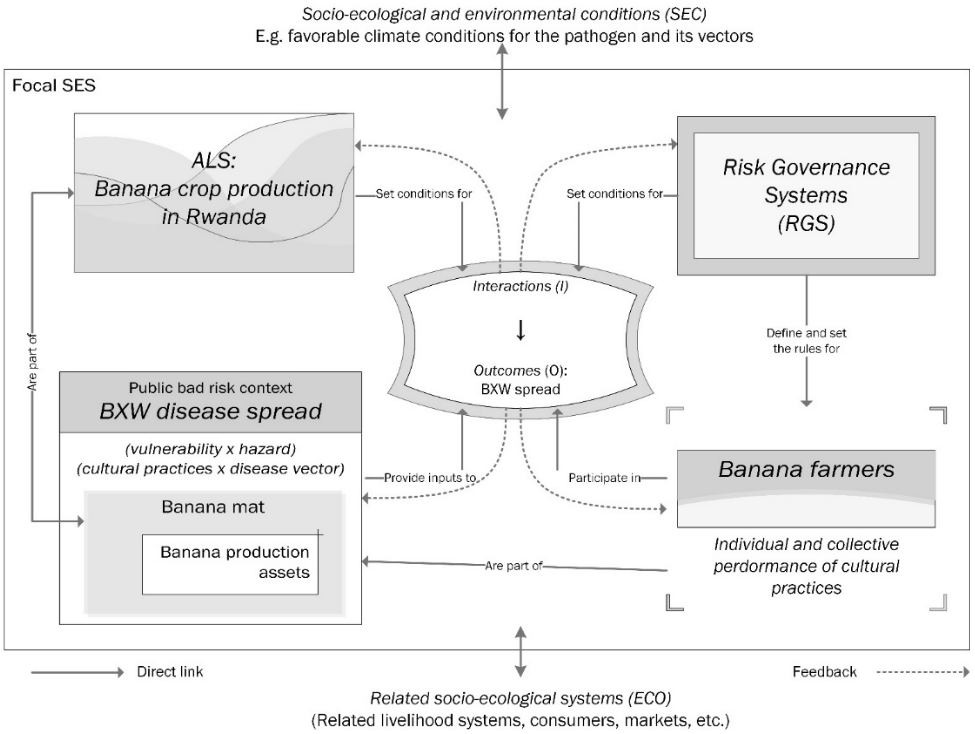


Figure 1. The core subsystems in a framework for analyzing a public bad risk (BXW disease spread) threatening agricultural livelihoods based on banana production in the context of a socio-ecological system from a risk and collective action problem perspective. Adapted from Ostrom (2007), Copyright (2007) National Academy of Sciences [10].

2.2. The Public Bad Risk Governance System: BXW Management in Rwanda

Governance refers to the actions, processes, traditions, and institutions by which authority is exercised and decisions are taken and implemented. Risk governance applies the principles of good governance to the identification, assessment, management, and communication of risks. The central risk under research in this study was the spread of BXW disease in Rwanda. BXW is caused by the *Xanthomonas vasicola* pv. *Musacearum* (previously *Xanthomonas campestris* pv. *Musacearum* [16]), and has the potential to cause banana yield losses of up to 100%. It is highly transmissible and can be easily spread through infected plant material, cutting tools, long-distance trade, and vectors such as birds, bats, and insects [17]. Vectors play an important role in disease spread, mainly through insects, birds, bats, and cutting tools (idem). Insects, for example, become vectors when visiting a male banana flower of a diseased stem to feed on nectar.

Rwanda's current policy for BXW disease outbreaks prescribes a practice called Complete Mat Uprooting (CMU). This involves uprooting the diseased stem and all lateral stems and shoots (i.e., the entire banana mat) regardless of their infection status. All uprooted material should be buried and covered with soil. Uprooting is advised to take place in an early disease stage to reduce further disease transmission. In high incidence cases (>70% of the banana mats showing symptoms), the whole plantation must be uprooted [18].

Although effective, CMU is also labor intensive, time-consuming, and socially costly and has therefore major implications for food and income production. It has an impact on livelihoods, making farmers reluctant to comply with good BXW management practices, which is further exaggerated by perceptions of the (in)effectiveness of disease management. Some farmers hide the disease by cutting down symptomatic stems or leaves to avoid enforced uprooting [19,20]. An alternative for CMU exists in the practice of Single Diseased Stem Removal (SDSR). In this case, only symptomatic infected stems, rather than entire mats, are cut, at soil-level. This method is low-cost, simple, and less labor intensive. SDSR is effective for bringing disease incidence to a minimum level and is especially suitable for smallholder farmers [21,22].

Regardless of the disease control practice, effective management always requires at least a combination of specific knowledge and know-how (e.g., to understand disease epidemiology, recognize disease symptoms, and uproot diseased stems), timely use of cultural prevention and control practices (e.g., planting healthy suckers, de-budding, disinfecting farm tools, and removing infected plants) and, preferably, coordinated collective action. A study in DR Congo showed the latter to be more effective for BXW control than individual action [23]. Additionally, the government needs to provide effective support mechanisms, e.g., advisory services and monitoring [20]. Hence, prevention of the spread of the disease can only be achieved (efficiently) if all the involved stakeholders work in a coordinated manner, something that comes with challenges regarding social dilemmas and effective communication strategies.

2.3. The Communication Variable in the Context of a Project

Data for our study were collected in villages belonging to a project in Rwanda: ICT4BXW. This project piloted a smartphone application (named BXW-App) and actively engaged with village-level extension agents to support the diagnosis and control of BXW in the country. As a project, ICT4BXW is just one example of many projects today that use digital technologies (e.g., mobile phones, sensors) and services (e.g., apps supporting virtual diagnostics, reporting, and surveillance of crop pests and diseases). Sometimes (partially) replacing face-to-face communication, digital communication services provide modalities to support the coordination of complex problems, such as management and control of crop diseases. While information, e.g., about effective detection, characterization, and quantification of an infectious disease (i.e., disease surveillance) is critical to design risk management strategies, it traditionally requires a costly and bureaucratic reporting chain [24]. Central to digital agriculture interventions is oftentimes a (smart)phone service (e.g., BXW-App in the case of ICT4BXW) that aids in the documentation and dissemination of agricultural information [25] and promises to enhance efficiency and effectiveness [26]. An acclaimed advantage of digital services over conventional face-to-face extension is that it allows for more personalization, adapting the service to the (farm) conditions of a specific, individual farmer [27]. This contrasts with the more one-size-fits-all character of traditional (public) agricultural extension services that are critiqued for not considering diversity among farmers and farms [28,29]. In Rwanda, for example, the provision of advice on disease prevention and control, as well as monitoring of and responding to disease outbreaks is the responsibility of Rwanda Agriculture and Animal Resources Development Board (RAB) on behalf of the Ministry of Agriculture and Animal Resources (MINAGRI). Through the country's extension system, activities such as group training on agronomic practices; diagnosing, reporting, and controlling pests and diseases; and information exchange during one-on-one and community meetings are organized. Within this context, space to adapt to an individual farmer's needs is limited, something digital agricultural services promise to respond to with tailor-made information and decision-making support that is given directly to individual farmers. Projects like ICT4BXW focus on communication mediated through digital technologies and services themselves. Yet, our implementation of the Musa-game draws attention to other dimensions of communication by visualizing the human-human and human-nonhuman interactions on the board, and the possibility to coordinate management strategies through communication during the game (see also Section 3).

3. Methods

3.1. Testing the Musa-Game in Rwanda and Exploring Data Analysis Methods

The Musa-game provides an abstract representation of the socio-ecological dynamics between a group of four farmers, their banana mats, the bacterial disease agent (BXW), the insect vectors transmitting the disease, and an external agent who monitors the spread of the disease [15] (PART I–Galarza-Villamar et al. 2021). Being real-life banana farmers, the players are confronted with a realistic representation of the problems of collective (in)action they face when preventing disease transmission. Operationalization of the Musa-game required the involvement of real actors faced with the social dilemma to adopt (or not) strategies to prevent or control a public bad threatening their livelihood. To make simultaneous agent actions and system outcomes possible, the experimental arena was a square-board that represented the biophysical space where, in real-life, actions and interactions take place. Additional (qualitative) tools, i.e., surveys and focus groups, were used pre- and post-experiment respectively to better understand context-specific motivations behind farmers' decision-making.

In April 2020, we tested the Musa-game in four villages of Kayonza district in Rwanda's Eastern province to identify possible needs for calibration and explore suitable data analysis approaches. Test games were carried out according to an experimental protocol with the support of trained research assistants speaking both the local language, Kinyarwanda, and English. In this section, we present the experimental treatments and the questions that we asked to evaluate the game design and treatments, and we then explore the qualitative and quantitative results from the test games.

3.2. ICT4BXW Project Context

The logistic arrangements for the field experiment test and sampling strategy were made in cooperation with the ICT4BXW project. ICT4BXW operated in 138 villages in eight districts, in four provinces, in Rwanda; 69 project villages are intervention villages where ICT4BXW piloted their smartphone application (BXW-App) and actively engaged with village-level extension agents (so-called farmer promoters). A farmer promoter (FP) is a village-level extension agent who is a farmer him/herself. Every village in Rwanda has an FP and he/she is the last-mile actor in the country's Twigire Muhinzi extension system [29]. An FP is elected by peer-farmers and the role is part-time and voluntary. BXW-App is a digital extension service that supports diagnosis and control of BXW (disease surveillance + early warning system), provides information about banana agronomic practices, and registers the local presence of BXW. Farmer promoters are the primary users of BXW-App. Secondary users of the information provided or data collected by BXW-App are farmers, researchers, and government representatives. ICT4BXW maintains partnerships with Rwandan government agencies (RAB and MINAGRI) because of those agencies' vested interest in reducing the impact of BXW as well as developing and maintaining successful digital agriculture solutions that respond to the country's policies [30].

3.3. Experimental Treatments

To contribute to understanding about the emergence and governance of conditions that hinder or improve the management of a public bad, we tested decision-making and actions of farmers toward governing a public bad risk: BXW disease. For the Musa-game, we chose to develop experimental treatments grounded in the communication principle of risk governance, as a central factor that affects different actor's (inter)actions with emergent outcomes. The communication principle can be defined as meaningful interactions in which knowledge, experiences, interpretations, concerns, and perspectives are exchanged (Lofstedt, 2003 cited by [31]) and provides a basis for governance decisions despite the possible presence of uncertainty, complexity, or ambiguity. Communication serves to share information about risks and create networks of trust and social support to find possible ways to handle (emerging) risks [32].

The three treatments were as follows: In treatment 1, players were not allowed to communicate during the game. In treatments 2 and 3, players had opportunities to communicate that allowed them to exchange their interpretations of the game, technical knowledge about and experiences with BXW disease, and perceptions of risk, as well as to develop an individual and/or collective risk governance strategy. In treatment 2, players were allowed to communicate before the first round of the game. This scenario is denominated as 'preventive communication' because players have not experienced the disease in the game yet. In treatment 3, players were given two communication opportunities: once before the first round (similar to treatment 2), and once in between rounds three and four (see also Table 1). The latter communication opportunity scenario is denominated as 'responsive communication' since it occurs when players are experiencing the spread of the disease and need to respond to the associated threats. Therefore, treatment 3 is a preventive-responsive communication scenario.

Table 1. Overview of sample used in the test experimental game.

Treatment	Boards	Description	Village	Part of ICT4BXW Project Intervention	Code Treatment/ ICT4BXW/ Board	N. Players
T1.a	Board 1 Board 2 Board 3.	Non comm.	Muzizi	Yes (a)	T1.a.b1 T1.a.b2 T1.a.b3	12
T2.a	Board 1 Board 2 Board 3.	Preventive comm.	Kamajigija	Yes (a)	T2.a.b1 T2.a.b2 T2.a.b3	12
T3.a	Board 1 Board 2 Board 3.	Preventive and responsive comm.	Kinunga II	Yes (a)	T3.a.b1 T3.a.b2 T3.a.b3	12
T3.b	Board 1 Board 2 Board 3.	Preventive and responsive comm.	Butimba II	No (b)	T3.b.b1 T3.b.b2 T3.b.b3	12
Total	12 boards 12 games	3 treatments	4 villages			48

From a methodological-analytical perspective, the test sought to explore:

- If the emergence of an event (throughout the game rounds) and its representation at a given place (the board) influenced players' decision-making (toward prevention and control of the disease, or institutional consequences of failing to do this) and vice-versa?
- If intertwined human and non-human dynamics influenced the creation of unfavorable collective conditions, either from the disease itself (death of the banana mat) or other associated ones (compulsory uprooting of infected mats performed by monitors)?
- If and how spatial analysis could contribute to the interpretation of the data collected through the Musa-game?

From the perspective of an experiment on risk governance, focusing on the principle of communication and its role in governing a public bad, the test sought to explore:

- If there was a difference in collective and individual performance in terms of net profit in the different treatments?
- If having previous knowledge of BXW disease management affected collective and individual performance in terms of net profit?
- If risk perceptions influenced participants' playing strategies for the prevention and/or control of a public bad risk such as BXW disease?
- If the experimental findings could inform digitalized disease management and communication strategies?

From a game mechanics design and contextualization perspective, the test also raised the following questions.

- Was the Musa-game easy to understand and attractive to play for actual farmers?
- Did the Musa-game sufficiently capture the real-life decisions about dilemmas related to the prevention and control of BXW disease?

The Musa-game test sessions had two phases: In the first phase, farmers played the game for up to seven rounds. In the second phase, players were involved in a focus group discussion. The quantitative and qualitative data were processed for spatial analysis. The dependent variables for analysis were the individual and collective profits, and the players' preferences to take risk management actions such as either cutting two flowers or uprooting one infected mat (Table 2). The spatial dimension of such decisions was considered by both tracing the position on the board and the round in which actions were taken.

Table 2. Dependent, independent, and controlled variables of the Musa-game experiment.

Dependent Variables	Independent Variables	Controlled Dynamic Variables
Individual profit outcome Collective profit outcome Decision to cut male flower (0 or 2 flowers per round) Decision to either cut male flower (0 or 2 per round) or uproot one infected mat.	Risk communication: none; preventative; responsive; preventative and responsive.	Farmer game rules Insect vector game rules Monitor inspection game rules Rules in the progression of the disease through the progress of time.

3.4. Sample

Test game villages were sampled based on the following criteria: location, agricultural activity, and reachability. The sample is not and was not intended to be representative since its purpose is limited to test experimental design, game design, and contextual coherence. A total of 48 male and female banana farmers participated in the test sessions, 12 farmers per session, with three individual games played per session. Farmers were randomly selected from a pool of 30 farmers per village whose names had been provided by the village leader or village extension agent. An over-sampling strategy was used to resolve potential no-show issues. For each session, 16 farmers were sampled, comprising 12 players and 4 reserves. In case a player farmer did not show up, he/she was replaced with a person from the reserve list. Persons on the reserve who were present but not needed as players were allowed to observe the game for learning purposes but could not contribute to the game or interact with the players.

To explore the effect of existing knowledge on BXW disease management on performance, we included two types of villages in our test sample: (1) those recently exposed to a BXW knowledge intervention and (2) those not exposed to a BXW knowledge intervention. Of the four villages, three (36 farmers) were villages that had interventions from the ICT4BXW project (intervention status–a). This project operated in Rwanda and developed and piloted a digital extension application specifically targeting BXW prevention and control. In these villages, the extension agent had received training about BXW through the project and used the extension application, and it could be expected that farmers had been exposed to the extension agent's knowledge about BXW. One village (12 farmers) was an ICT4BXW control village where no previous project interventions had taken place (control status–b). Each participant provided their informed consent and agreed to participate in the Musa-game (Table 2).

3.5. Procedure

Each treatment was tested with a game session taking approximately 2 h. In each session, three games were played with four players each. Every game table had two research assistants, one game master, and one note-taker. The gameboards and their components (e.g., cards) were placed on separate tables. For each session, a sticker with a unique identifier code was placed on each of the four gameboard quadrants with each identifier being randomly assigned to a participant. A camera was attached to a tripod with a horizontal arm to video-record the game (Figures 2 and 3). This overhead setup only recorded the boards and the players' hands during the game rounds, guaranteeing player anonymity. As part of the informed consent, players consented to the session being video and audio recorded.

Figure 2. Test session in Kayonza. In the picture, four farmers are playing the board game (**a**) while being recorded (**b**).

Figure 3. Test session in Kayonza with three groups of players with a distance between the game tables. Separate video equipment (**a**) and game kits (**b**) were used for each table.

After welcoming a participant, a research assistant would lead them to the seat matching his or her identifier. Once all players were seated, the session started with a general introduction about the Musa-game (i.e., BXW disease, the research project, and the objective of the game test). The research assistants then explained the rules of the game in Kinyarwanda, supporting their explanations with demonstrations on the actual board. Participants had the opportunity to play one trial round and ask questions or for clarifications afterward. Thereafter, the game started following the specified treatment protocol.

For each test-game the coordinates of both monitor and insect were assigned randomly in advance, using statistical software, and were equal for every session. In every round, the farmers first decided if and which action they should take. After that, the game master announced the location of first the monitor and then the insect and placed it in the right cell on the board. In each round, the assistant read aloud the position on the board where the monitor and insect card will visit. The players only know where the insect and monitor will visit after they have made their decisions. The notetaking research assistant, meanwhile, filled a paper-based form to track the farmer/players' actions, the monitor's and insect's locations, and the intermediate game outcomes. The video and audio recordings of the session were used as a backup to the hand-written data.

4. Result and Analysis

In this section, we explore the test game results, both quantitatively and qualitatively. First, we assess game acceptance, game vs. real-life practices, and perceptions about the different treatments. We then look at how results from the Musa-game may inform us about individual and collective benefits and possible relationships between benefits and individual decisions regarding what action to choose, and where to spatially perform that action. Lastly, the section looks at learning effects. Given the small sample size and the exploratory nature of the analysis, we did not perform any inferential statistical analysis, but used descriptive statistics and descriptive spatial analysis.

4.1. Participants Receptivity to the Musa-Game

The responses from the banana farmers who played the Musa-game showed that it was well-received and mostly understood by players. Participants expressed gratitude for the game's learning effect: *"Before we'd cut flowers and even uproot the infected bananas but without knowing the reasons why we do that. But after playing this game we understand the importance of cutting flowers and uprooting the infected banana mats"* (T3.b.b2). We also found evidence of social learning mechanisms, especially regarding fighting BXW collectively: *"This game taught us about the way that we should work together with our neighbors when fighting BXW"* (T2.a.b3); and *"After playing this game, I recognize that a better way to eradicate BXW disease is to collaborate with my fellow banana farmers by advising each other"* (T3.b.b2).

Participants perceived the game as a fun way to learn about BXW disease by playing the game and interacting with their peers. A farmer noted that: *"The game was fun, and [it was] interesting to understand what was happening and why"* (T2.a.b1). Farmers mentioned that playing the Musa-game helped them to understand the consequences of their actions: *"The game was amazing, and we have seen that it is better to prevent BXW disease because if we don't do it, we lose our investment too (T2.a.b2). Others acknowledged the importance of working together "The game showed me that working together is very important in fighting BXW"* (T1.a.b1).

Farmers reported that the Musa-game equipped them with relevant skills: *"Honestly I am happy that you gave us these priceless skills on the importance of cutting banana flowers. I wish you could come as many times as you can and teach us more"* (T1.a.b1) and said that they wanted to share this knowledge with other farmers, with one suggesting *"What I get after playing this game, I am going to teach all of these good lessons to my neighbors so that we can work together in combating BXW disease"* (T2.a.b2) and another mentioning *"What I can give as an advice is that you need to reach out to every banana farmer in the country, to make them understand how to prevent this dangerous disease and the importance of working together"* (T1.a.b1).

From a disease management perspective, participants mentioned learning from both the Musa-game rules and discussions with their peers: *"What I learned [...] is to share ideas as neighbors by reminding each other to visit each other's fields more often. In addition, [...] I learned [...] that we should invest in protecting our banana fields"* (T3.a.b3). Some participants were unaware that the BXW could be transmitted by insects and therefore had not prioritized cutting flowers in their fields *"[...] I learned that BXW disease is caused by an insect, this has led me to decide to wake up early every day to visit my field and cut flowers"* (T3.b.b2).

Farmers agreed that the Musa-game is a helpful tool to develop a better understanding of both the disease and the impact that individual actions can have for collective benefit: *"BXW is a very bad disease which can cause a big loss, not only to an individual farmer but also to the whole village and our country. In order to solve the problem of BXW disease, it is better to mobilize our fellow farmers [...] through village meetings"* (T3.a.b2). Moreover, the importance of preventative actions for protecting fields and livelihoods became clear: *"What I learned from this game is that we should cut flowers early and uproot the diseased mats immediately"* (T1.a.b3); and *"What I observed through this game is that if we don't protect our fields from BXW it will cause poverty"* (T3.b.b3).

4.2. Participants' Perception of How the Game's Representation of Decision Dilemmas to Prevent and Control BXW Disease Accorded with Real-Life

Participants accounted that BXW disease is a recurring issue in their lives: *"The game tells me how to fight BXW and this is a real problem that I have been fighting with for four years"* (T1.a.b2). They also related the game context to their real-life experiences with BXW disease prevention and control: *" ... in this game those who did not invest in protection faced losses. The same happens in real-life, if you don't invest in protecting your field then you lose"* (T3.a.b1).

The Focus Group Discussion (FGD) data provide insight into participants' knowledge about cultural practices used to prevent BXW transmission. For example, most players were aware of the practice of cutting the flower: *"The decisions about cutting flowers and uprooting the diseased mats that I had to take in the game were the same as the ones I'm used to taking in real-life"* (T3.b.b3). Others coped differently with diseased mats in real-life: "*I'm used to cutting the diseased mat and leaving it in the field, not to uprooting it* (T2.a.b3). Some participants displayed knowledge about other disease infection mechanisms and prevention practices: *"I can also get infected by using infected tools like hoes, machetes, or get infected by my neighbor who has BXW in his field"* (T2.a.b3), and *"[In real-life] I have also observed that even bananas which have no flowers are also infected by BXW. So, since you are researchers, I would like you to take this into consideration too"* (T3.a.b3).

Farmers who played in one of the two different game treatments with communication (T2–T3) told us that the risk communication style during the game differed from real-life:

> *The style of communication during the game was not the same as the one we use in real life, because when you meet someone, the only thing you tell him is if you have been infected by BXW. [...] we never discuss together the measures we should take to fight this disease. But during the game, I was able to discuss and share with my neighbours the measures that we can take to fight this disease together.*
>
> (T3.a.b3)

Participants experienced this communication as providing an opportunity to learn from others and develop strategies to fight BXW together: *"We also discuss about BXW in real-life but there is a small difference, [in real-life] we might see our neighbor's field infected by BXW but do nothing to help, but during the game, we discussed [...] what we should do"* (T2.a.b3).

Farmers playing the non-communication treatment (T1) thought that communication was crucial to make better decisions: *"I wished to share ideas with my friends. I even whispered but you caught me and stopped me"* (T1.a.b1). According to T1 players, communication would not only allow them to make better individual decisions but also collectively respond to a common threat: *"I think that if we'd had a chance to discuss during the game, I would not have been infected by BXW because we would take action together to fight this disease"* (T1.a.b3).

4.3. Overall Game Performance

Figure 4 shows the results from all 12 boards in terms of net profits. In 100% of the games, collective food security and some net profit from banana production were achieved. Individually, only one player, in T3.b, ended the game with net debt and became food insecure. The mean average was similar for all games, ranging between Fr. 4000 and Fr. 4650 for 10 out of the 12 games. Hence, descriptively, we observed no significant profit differences between the treatments.

Figure 5 provides information about differences in the actions that players prioritized in the different treatments. In T1.a and T3.a, none of the farmers ended the game with cards representing a risk for themselves or their neighbors (i.e., yellow or red cards). In T2.a and T3.b, some players ended the game while there was still a disease threat (i.e., a yellow and red card in T3.b and a yellow card in T2.a).

4.4. Spatial Locations of Decision-Making: Decisions about Where to Cut Flowers

Since the Musa-game is played on a board, there is a spatial dimension to players' decision-making. Each player shares their quadrant's inner border with the other three players. However, the game instructions did not inform players about what would (hypothetically) be adjacent to the outer borders of their quadrant. The hypothesis is that farmers who decided to take preventive (cut flower) or responsive (uproot diseased mat) action nearer to the inner border (=their fellow players) showed more cooperative behavior than farmers who took actions nearer to the outer border. This is because the game rules informed players that their actions can have consequences for both themselves and their fellow players. For data analysis purposes, we transcribed the original notation of the board locations from letters and numbers to just numbers (Figure 6). Locations 1 to 5 adjoin the four players, 9 is the location furthest from the board's center, and 6–8 sit in between.

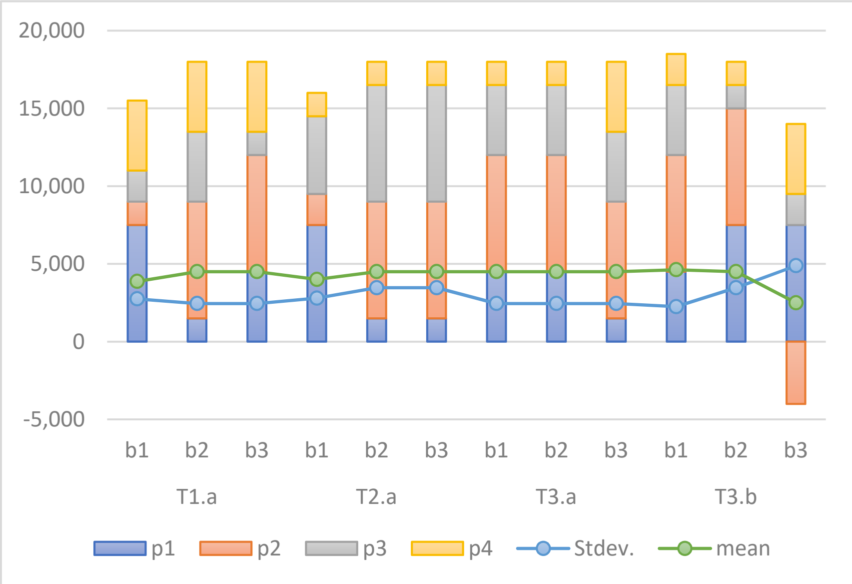


Figure 4. Game results expressed in terms of profit per player, per board (four players/board), and per treatment (three boards/treatment). The blue line represents the profit standard deviation per board. The green line represents the mean profit per board.

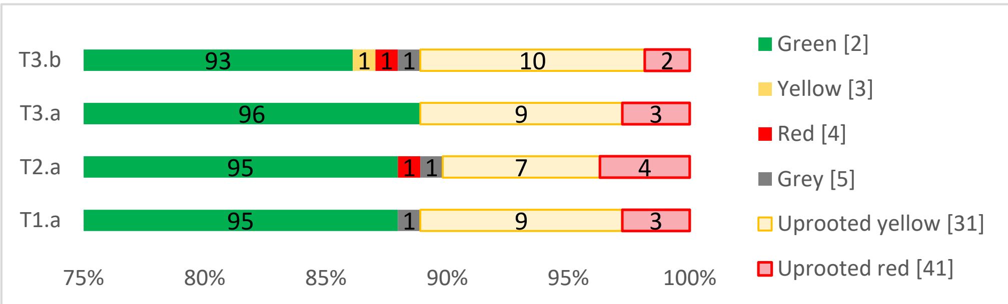


Figure 5. Type of cards that remained on the board at the end of the game, presented in percentages, and which determined players' profits: Green card (healthy mat without flower—code 2), Yellow card (BXW infected mat, first disease stage—code 3), Red card (BXW infected mat, second disease stage—code 4), Grey card (dead mat—code 5), Uprooted yellow card (code 31), Uprooted red card [code 41].

Figure 7 shows the board locations where players cut flowers to prevent BXW transmission in each round. In all four treatments, players cut flowers in locations 4, 5, 8, and 9 in round 1, which are mainly outer border locations. The mats in those locations never got infected. Location 3 (the most central) was cut in the first two rounds mainly by farmers in T3.a, the treatment with farmers exposed to knowledge about BXW in real life and with two opportunities to communicate during the game. Only in T3.b (groups with two communication opportunities that do not belong to the ICT4BXW project) did none of the players cut flowers in the most central locations (1–5), while it took until round 4 before the central location (3) was cut.

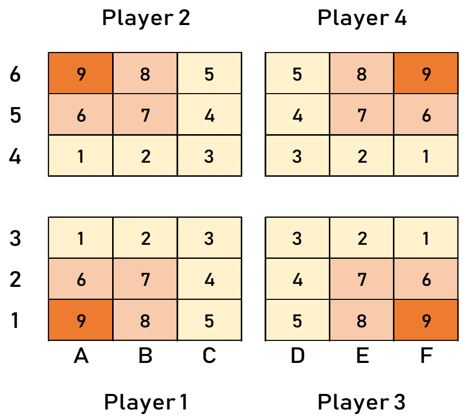


Figure 6. Game board map: players' positions and mat locations for data processing purposes.

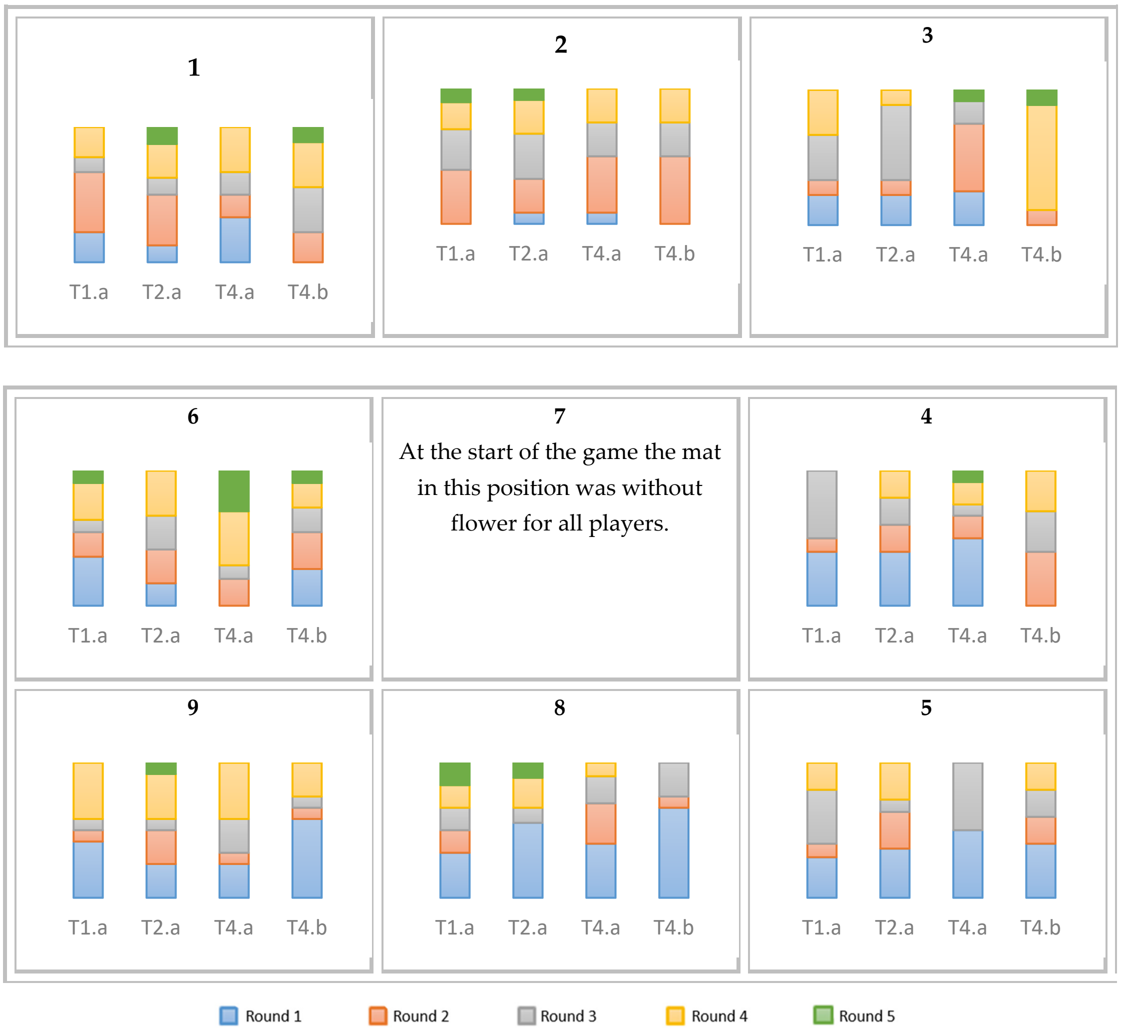


Figure 7. Proportion of decisions to cut flowers taken in the nine board locations in each game round. The figure is presented like a player's section of a board from the perspective of player 1 (see Figure 12). Each segment is numbered from 1 to 9, corresponding with locations. Locations 1–5 are the board's inner borders. Location 3 is the most central location on the board. Location 9 is the board's outer corner. The bar diagrams within each segment show the proportion of flowers cut in each round per treatment. E.g., in round 1 (light blue color), many flowers were cut in position 9, the location farthest from the board's center, and only a few in position 3, the most central location. Location 7 does not show data because all players started the game with a mat without a flower in that location.

Although players in T3.a and T3.b had the same communication opportunities, there were differences in the flower-cutting locations between rounds. The players in T3.a had been exposed to knowledge about the disease in real-life and this may have influenced their ability to communicate about prevention and control practices and work out a (spatially) more cohesive game strategy.

4.5. Spatial Distance-Based Decision-Making Analysis: The Musa Analysis Tool

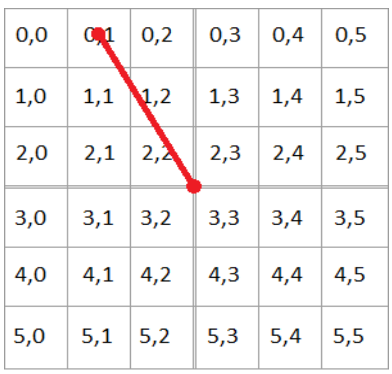
To retrieve the results presented in the following sub-sections, a computational program, called the Musa analysis tool, was developed to assist with analyzing our dataset which includes both decisional and spatial dimensions. The Musa analysis tool was developed using the programming language C Sharp (C#) and its task is to perform different spatial analyses based on distances and relate those to game decisions. The software assumes a uniform distance of 1 × 1 unit between the banana mats (positioned in a segment), and its point of interest is in the central position of each segment (Figures 8 and 9). The distance between two random points A and B is given by (Equation (1)):

$$D = \sqrt{(PI_{Ax} - PI_{Bx})^2 + (PI_{Ay} - PI_{By})^2}, \tag{1}$$

where *PI* is the position of interest for calculation measured from the center of each segment.

Likewise, all the distances measured during the experiment correspond to the distances between a PI (Point of Interest) of a segment, corresponding to the player's actions, and another PI of a second segment, corresponding to a direct value of the board at that instant of time (Game Round), or the Pc position (Center position). These measurements were normalized to a scale of values between 0 and 1, which will mean a value of 0 for positions outside the board and 1 for positions where specific actions are taken.

The distance given in values between 1 and 0 is called the normalized distance, or Dn, and is given by $Dn = \frac{(Dm-D)}{Dm}$, where Dm is the value of the maximum possible distance between two ends of the board. For calculations where the only reference is the Central Position (Pc), the Dm is half the diagonal of the board. For practical purposes, it should be emphasized that during the real measurements, for normalized distance (Dn), the closed values of 1 and 0 are be represented (see the Supplementary Materials for detailed information on the software methodology).



$$D = \sqrt{((0+0.5)-3)^2 + ((1+0.5)-3)^2} = 2.91$$

Figure 8. Distance calculation between a random point (0,1) and Pc (Central Position). Notation for each segment is given in coordinates X, Y.

0.17	0.31	0.40	0.40	0.31	0.17
0.31	0.50	0.63	0.63	0.50	0.31
0.40	0.63	0.83	0.83	0.63	0.40
0.40	0.63	0.83	0.83	0.63	0.40
0.31	0.50	0.63	0.63	0.50	0.31
0.17	0.31	0.40	0.40	0.31	0.17

Figure 9. Example of the initial board situation in the Musa analysis tool. It shows the values of the Normalized Distance (Dn) for each segment surrounding the Central Position (Pc) of all types of mat's states (healthy, infected, intervened, or dead) for a standard board in the initial round.

4.5.1. Decision to Cut Flowers in Relation to the Minimum Distance to a Neighbor's Mat without Flower

Figure 10 shows the relationship between the proportion of flowers that players cut and the minimum distance to a neighbor's mat without flowers (green card). The closer the flower cutting action was to a neighbor's green card, the closer the distance value was to 1. The graph shows, in intervals of 0.1 distance units, the proportion of actions taken at distances between 0.1 and 0.9. It can be observed that in the complete sample, indifferent of treatment, the decision to cut a flower in round 1 started at a distance of 0.5 (in relation to the nearest green card). It thus appears that participants' flower-cutting actions were not oriented toward forming clusters of green cards in the center on the board, but dispersed in directions closer to the board's outer borders.

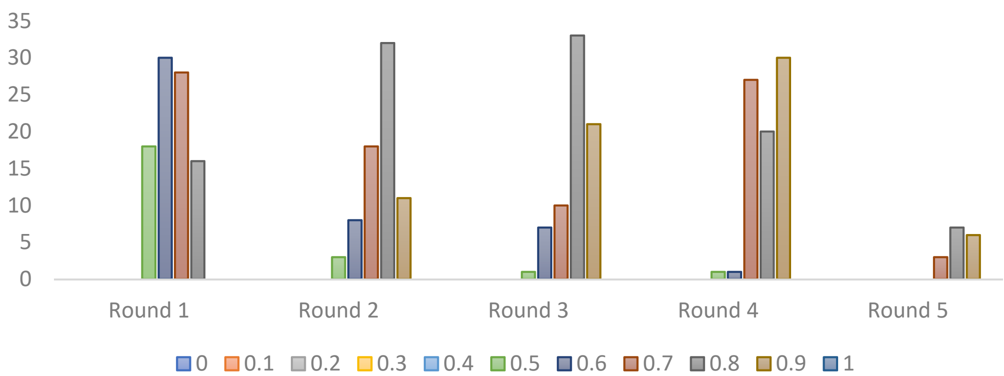


Figure 10. Number of flower-cutting actions versus the minimum distance to a neighbor's mat without a flower. Distances are shown in intervals of 0.1, from 0 to 1. The distance closest to 1 represents the shortest distance to a neighbor's mat without a flower.

As the games progress, the number of green cards on the board can be expected to increase. Therefore, in round 5 we can see that flower-cutting decisions all happened at distances of 0.7 and above (i.e., close to a neighbor's green card).

When asked about the action to cut flowers during the FGD, participants agreed that cutting as many flowers as possible was the best preventative game strategy: *"I cut flowers because when the insect that spreads the disease arrives and finds that the bananas are protected, it will leave and infect where the bananas are not protected"* (T3.b.b3) and that a regular reminder is desired: *"[. . .] it is always good to keep reminding our neighbors to cut banana flowers in their field"* (T2.a.b2).

4.5.2. The Decision to Uproot Yellow or Red Mats Versus the Minimum Distance to a Neighbor's Healthy Mat with or without Flower

Although cutting flowers close to where neighbors also cut flowers did not appear to be a priority for players, uprooting diseased mats did. Even though the monitor did not intervene in any of the game sessions, there was a general perception of risk regarding the monitor finding an infected mat: *"I was afraid that if the monitor came and found that there was a disease in my mat it would have been necessary for me to uproot other bananas near the sick one. But I was lucky enough to get rid of it before he arrived"* (T3.a.b1); and *"I feared that the monitor might come and punish me for infecting my neighbors' bananas"* (T3.a.b2). Figure 11 shows the proportion of yellow cards that were uprooted and the distance to a healthy mat (with or without flower, white or green card). The nearer a player's yellow card was to a neighbor's healthy mat, the closer the distance value was to 1. Positions over 0.8 are the immediate neighbors' locations. Overall, we observed no actions at distances below 0.7. If we relate this to the locations where players cut flowers (with a tendency to cut far from neighbors), it implicitly tells us that most mats vulnerable to disease infection (=white cards) were located near the center of the board. Thus, if one of those mats becomes BXW infected (yellow card), it is located close to healthy mats and is therefore more of a collective threat for all players.

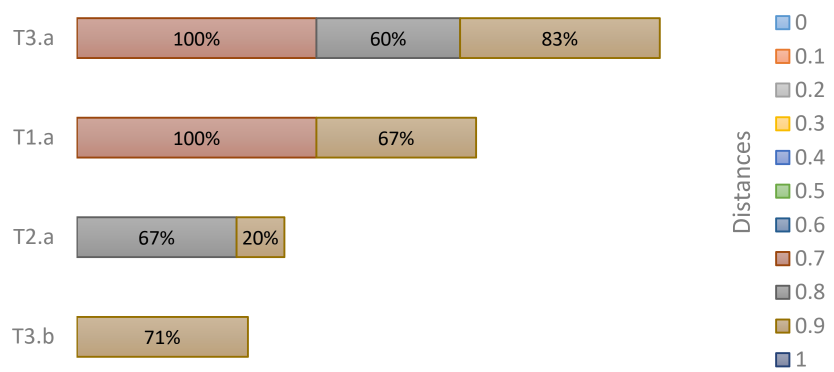


Figure 11. Stacked bars showing the proportion of uprooted yellow mats in relation to the minimum distance to a neighbor's healthy mat with or without a flower. Distances are between 0 and 1, in intervals of 0.1. Distance closest to 1 represents the shortest distance to a neighbor's mat with/without a flower. E.g., players in T3.b uprooted a yellow mat 71% of the times that it was located at a 0.9 distance from a neighbor's healthy mat. This means that the remaining 29% of yellow mats became a red mat in the next round, if not visited by the monitor.

Players in T1.a and T3.a uprooted infected mats more often than they cut the flowers. FGD data confirmed that for those playing in T3.a, uprooting infected mats was the main strategy *"We uprooted mats of infected bananas to protect the remaining bananas in the field as we have realized that if we do not uproot early the banana might turn to red which can be dangerous not only in my field but also for my neighbors"* (T3.a.b2). These players prioritized uprooting diseased mats over profit-making: *"Although some of us did not get much profit we have at least managed to uproot the infected mats"*. They also worked together to minimize overall losses: *"We tried to work together as a team so that no-one would suffer a loss"* (T3.a.b2). Players in T1.a uprooted yellow mats 100% of the time when they were in a position of 0.7 from a neighbor's healthy mat and 67% of the time when they were in a position or 0.9 distance from a neighbor's healthy mat. Players in T3.a uprooted yellow mats 60% and 100% of the times when they had them in the same positions. In T2.a and T3.b, the action of uprooting yellow mats decreased to less than 71% when infected mats were located more than 0.8 distance from healthy mats. This means that some players let their yellow mats progress to red (second disease stage) and that T3.b players, in contrast to those in T3.a., prioritized cutting flowers over uprooting infected mats: *"I cut all the male flowers in my field and uproot later"* (T3.b.b2).

Of the mats progressing from yellow to red (Figure 12), players in T3.a uprooted 100% of the time when a mat progressed to red, and these were located at an average distance of 0.8 distance to a neighbor's healthy mat. In all other treatments, the decision of uprooting a red mat was under 75%, meaning that the players allowed the disease to progress from a red to a dead stage (grey card). While not uprooting a yellow mat was a risk for the individual player, not uprooting a red mat put all the players at risk of uprooting if it was found by the monitor. Players in T3.b., who were not part of the ICT4BXW project intervention, took the highest collective risk.

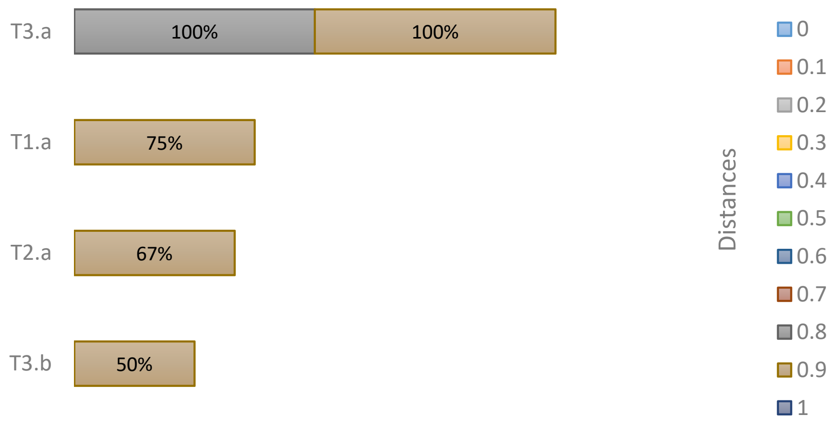


Figure 12. Stacked bars showing the proportion of uprooted red mats in relation to the minimum distance to a neighbor's healthy mat with or without flower. Distances are between 0 and 1, in intervals of 0.1. Distance closest to 1 represents the shortest distance to a neighbor's mat with/without a flower. E.g., players in T3.b uprooted a yellow mat 50% of the times that it was located at a 0.9 distance from a neighbor's healthy mat. This means that the remaining 50% of yellow mats died in the next round, if not visited by the monitor.

4.5.3. Decisions about Cutting Flowers and the Distance to an Infected Mat and the Outer Border

We also explored the relationship between the decision to cut flowers and the distance to two different variables: distance to the outer border (distance toward 0), and distance to the nearest infected mat (yellow or red) of a neighbor (distance toward 1). If the player decided to cut a flower closer to the outer border rather than closer to the nearest infected mat of a neighbor, the value was closer to zero. If the player cut a flower closer to the infected mat, the distance was closer to 1. In Figure 13, we see that 66% of players cut the flowers closer to the border, and only under 10% cut flowers in positions near a neighbor's infected mat. These results suggest that players preferred to invest in cutting flowers in positions the farthest from an infected mat. The fact that most farmers decide to cut flowers in positions 0.2 distance from the border (close to the outer border, far from the neighbor's infected mat) suggests that most infected mats are located toward the center of the board.

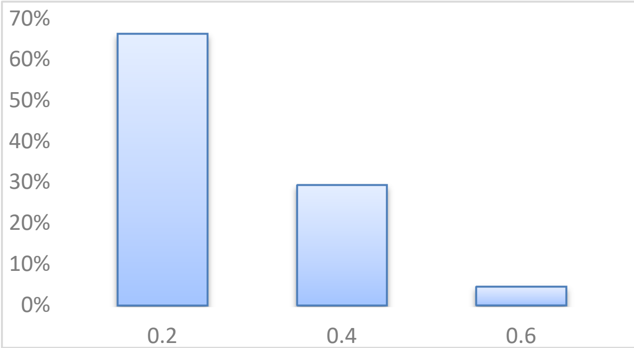


Figure 13. Decision to cut flowers in relation to the distance to the outer border and infected mats. The *X*-axis shows the distances between the outer border (toward 0) and an infected mat (toward 1). The *Y*-axis shows the proportion of flower-cutting actions in between both variables (outer border and infected mat).

4.6. Exploring the Usefulness of Neighbors' Analysis

We used the Average Nearest Neighbor Distance tool available in ArcGIS to perform exploratory analysis and calculate the expected mean distance between each feature and its nearest neighbor's location. The feature, in this case, represents the location of a banana mat and its nearest neighbor's mat where a player took an action (either cutting the flower or uprooting an infected mat). The expected distance is based on a hypothetical random distribution with the same number of features covering the same total area [33]. To make this analysis possible, we gave a hypothetical geographical coordinate to each location, with a homogeneous distance in meters between features. The purpose of this analysis was to explore the relationship between the progression of the distance between actions taken over time and a player's net income. Our assumption is that the larger the distance in the first rounds, the less cooperative a player's actions (=farther away from the board's center), resulting in lower, or more unequal, individual net incomes.

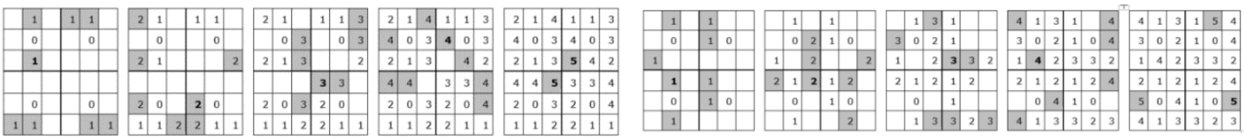
We tested this analytical method comparing T2.a and T3.a. As previously described, players in T2.a had one communication opportunity before the start of the game (preventive), and players in T3.a, had a communication opportunity before the first round (preventive), and after the third round (responsive). Players involved in both treatments belong to a group of farmers that are part of the ICT4BXW project, which provides them with training in BXW management. In Table 3a, we see that the mean net incomes were very similar, although the income per player varied. Players 1 and 4 in game T2.a. made a net income of 16,500 Fr., while players 2 and 3 ended the game with a net income of 22,500 Fr. In T3.a, the variation among players' net income was lower, with three out of four players gaining net incomes of between 19,500 and 22,500.

In Table 3b, the board locations where the action took place are shown progressively from round 1 to round 5. The numbers (from 1–5) shown in each square denote the round where the action was taken. The actions were either to cut flowers or to uproot an infected mat. We see that players 1 and 4 from T2.a, with the lowest net incomes, initially chose to take these actions in more distant locations but that they became closer to the center as the game progressed. The final actions of those players (round 5) were in the board's central locations. Players in T3, in contrast, starting from round one took actions closer to the center of the board and ended the game toward the outer border of the board, hence working in a closest to furthest distance order.

Table 3. Relating expected mean distances to net income standard deviations across five rounds.

	Treatment 2.a: Preventive (26)						*Treatment 3.a: Preventive-Responsive (28)*					
	T2.a	*r1*	*r2*	*r3*	*r4*	*r5*	*T4.a*	*r1*	*r2*	*r3*	*r4*	*r5*
a	*P1*	*23,100*	*20,300*	*19,800*	*17,000*	*16,500*	*P1*	*23,100*	*20,300*	*19,800*	*19,600*	*19,500*
	P2	*23,100*	*22,900*	*22,700*	*22,500*	*22,500*	*P2*	*23,100*	*22,900*	*22,700*	*22,500*	*22,500*
	P3	*23,100*	*22,900*	*22,700*	*22,500*	*22,500*	*P3*	*23,100*	*22,900*	*20,100*	*19,600*	*19,500*
	P4	*20,500*	*20,000*	*17,200*	*17,000*	*16,500*	*P4*	*20,500*	*20,000*	*19,800*	*17,000*	*16,500*
	Mean	*22,450*	*21,525*	*20,600*	*19,750*	*19,500*	*Mean*	*22,450*	*21,525*	*20,600*	*19,675*	*19,500*
	Sum	*89,800*	*86,100*	*82,400*	*79,000*	*78,000*	*Sum*	*89,800*	*86,100*	*82,400*	*78,700*	*78,000*
	Stdv.	*1300*	*1592*	*2647*	*3175*	*3464*	*Stdv.*	*1300*	*1592*	*1407*	*2247*	*2449*

b



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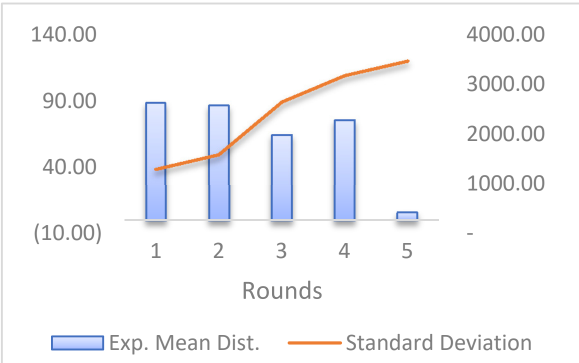

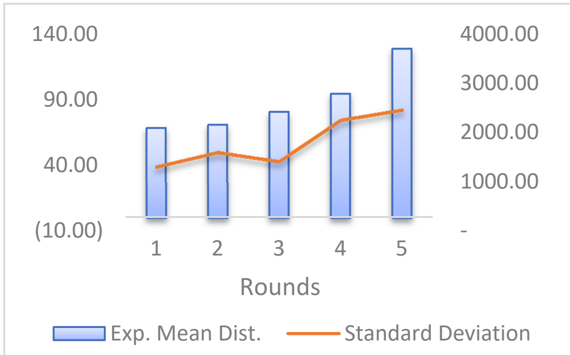

In Table 3c, we relate the expected mean distance between the location where actions were taken (features) in each round to the standard deviation of the net income across rounds. Looking at T2.a, we can see that the lower the distance among the positions where the actions were taken toward the game's end (round 5), the higher the standard deviation of the net income (3464 Fr). In T2.a, the distance among action-taken positions remained dispersed up to round 4 and did not show a trend. In T3.a, we see that the distances increased steadily as the game progressed, resulting in a lower standard deviation of net incomes (2449 Fr). These differences (in trends) between the treatments might be related to players in T2.a not having a communication opportunity between the rounds. This meant that players in T2.a players did not exchange any information that could have contributed to the emergence of a different strategy once the game started.

In public bad management terms, the results suggested that more communication opportunities contribute to better collective management of risks. Secondly, they suggested that collective action in risk management can create socio-ecological conditions for a more equal distribution of benefits.

5. Discussion and Conclusions

5.1. The Emergent Phenomena and Spatial Analysis to Better Understand Public Bad Risks

This paper built upon Ostrom's SES framework (2007) [10], a framework for analyzing a public bad risk threatening livelihood resilience, from a risk and collective action problem perspective and presented results from field-testing an experimental board game: Musa-game. The game method emphasizes the role of emergent phenomena in decision-making, which were operationalized for the context of BXW disease management in Rwanda. With the Musa-game, we successfully added the element of emergence to the study of public bad risks and showed how various interactions between entities (i.e., players, insect vectors, and monitors) and their individual decisions, and rules of the socio-ecological system give rise to unpredictable and interdependent risk scenarios. The combination of autonomous players, emergence, and spatial analysis in the Musa-game elicited a metacognitive experience for players. Individual players (farmers) needed to adapt to the emerging conditions through individual and collective actions towards coordination of the disease risk. By tracing the data about the what, where, and when of player's management decisions, we were able to better understand how decisions shape the public bad risk in different circumstances. Through the Musa-game, we traced data showing the BXW disease prevention and control decisions that players took. We also looked at the timing (game rounds) and locations (on the game board) of those decisions. The analysis allowed us to link, through spatial analysis, decision-making and risk scenarios that emerged from the decisions of players, together with actions of autonomous entities (insect and monitor). The potential causal relations we identified helped us to develop hypotheses about the decisions made in different communication scenarios.

5.2. The Influence of Knowledge and Communication

Exploring the number of decisions to cut flowers closer to the outer border or a neighbor's infected mat, we found that over 60% preferred to cut flowers in mats that were further from a neighbor's infected mat. FGD data suggest that farmers perceived proximity to a sick mat as high risk: *"Although I was in the favorable condition of not being infected by BXW in my field because I cut my flowers frequently, I feel like I still risked BXW infecting in my field because my neighbors had BXW disease in their field"* (T3.b.b2). This suggests that farmers fear making an unworthy investment (cutting flowers) near an infected mat. Farmers experienced uncertainty about whether their neighbor would choose to uproot their infected mats, or to cut more flowers: *"Even though I already cut all my flowers I was still afraid because the neighbors still had BXW in their field"* (T3.a.b1). Additionally, at least some participants knew that disease transmissions patterns other than insects exist, albeit these were not included in the game: *"I can also get infected through using infected materials like hoes, machetes, or get infected by my neighbor who has BXW in his field"* (T2.a.b3). Therefore, cutting flowers near a neighbor's infected mat presented a higher investment risk since, if not uprooted, that disease mat could be visited by the monitor resulting in loss of both mat and investment. Thus, risk perceptions about infected mats and the neighbor's decisions about uprooting probably contributed to sustaining the dispersed strategy.

The game strategy adopted by participants was similar across all treatments. However, we found that, over time, the strategy changed in groups that had both previous knowledge about disease management (because of being an ICT4BXW intervention village) and multiple opportunities to communicate (treatment 3) and became more cooperative. Players from T3.a had some previous knowledge of BTW disease management and had two communication opportunities during the game. A farmer said: *"If there was no communication, I would not know what measures I should take, and the result would have been a big loss"* (T3.a.b3). These game tables had the highest proportion of uprooting of yellow mats during the game and uprooted 100% of the red mats. Although they initially started cutting flowers closer to the outer border, this changed from round 2 onwards, when players started cutting flowers closer to their neighbors (Figure 13).

Although participants in T3.b also had two communication opportunities, their management strategy for preventing disease spread was the least effective. This was the only game in which one player ended up in debt. The playing strategy was focused on the outer borders, and the games ended with more infected mats in the yellow and red stages, representing a collective risk. The relationship between the number of infected mats uprooted and the distance to a neighbor's healthy mat was the lowest (see Figures 11 and 12). One difference between groups T3.a and T3.b was previous disease knowledge. Participants in T3.b were not involved in the extension service program that provided training in BXW disease management since they were an ICT4BXW project control village. The result suggests that the absence of, or incorrect, information has the potential to create greater collective risks.

6. Reflection on the Musa-Game Method

6.1. The Observed Phenomena in the Game

Based on the quantitative and qualitative results, we observed that most players, in all of the treatments, started the game by cutting flowers from the outer borders. We interpret this strategy as a non-cooperative one since it creates conditions that increase collective risk. However, why did farmers choose this strategy? When explaining the game's rules and structure, the research assistants explained that the monitor would randomly visit one mat in each round. Players were not told where the monitor came from or where he/she would go after visiting a mat. Yet, FGD data suggests that farmers assumed that the monitor watched their actions from somewhere, even when the monitor card was not yet played: *"I felt I was at a high risk because the monitor was somewhere watching or circulating"* (T1.a.b1). Therefore, players tried to first satisfy their need to decrease the threat of the monitor if he/she would watch their poor performance on disease management. This suggests that farmers supplemented the information gaps with their personal experiences about (disease) monitoring in real-life. This is not unlikely given the high level of social control and hierarchical structure of Rwandan society, where any person might report about events in their community to a local leader or extension agent. Thus, monitoring is not a foreign concept to farmers. Additionally, we know from reports of extension staff that farmers sometimes 'hide' diseased bananas by being more rigorous in their agronomic practices in places that are visible from the road or close to houses in an attempt to be seen as a 'good farmer'.

Since the players started the game by cutting flowers mostly toward the outer border, mats in the most central locations were vulnerable to infection by insects for a longer period. The strategies for cutting flowers varied across the treatments. For example, players in T3.a tried to satisfy both the need to show good agronomic performance to outsiders and decrease collective risk. They cut one flower near the border and one flower near the center. By contrast, players in T3.b focused their flower cutting in locations toward the board's outer border. This (initially) individual strategy created a collective risk and mats in more central positions started to get infected over time.

6.2. Reflection on the Game's Results

Our study results suggested that for effective collective management of public bad risks, a farmer needs to have both the right knowledge and the opportunity to build a collective strategy. This finding aligns with [34], whose authors found that the provision of technical information about disease managerial practices alone can have a counterproductive effect on disease management decisions. On the other hand, a combination of both information provision and opportunities for communication and internal governance can lead to better decision-making.

Risk perception appears a critical factor. Participants in this study designed their playing strategies based on their perceptions of risk, either from the fear to be found underperforming by the monitor 'watching them from somewhere', or the possibility that their neighbors do not take actions that reduce the collective risk. Consequently, the sum of the individual decisions to take actions closer to the board's outer border not only created a collective risk but, in some cases, also became a self-defeating decision. Thus, the completeness and quality of the information provided matter. In the absence of complete and trustworthy information, self-defeating strategies may be created, especially when the decisions are taken in a vacuum without consultation, and deliberation, with peers. COVID-19 is one example of the influence of misinformation (or a lack of information) and inaccurate risk perceptions. The rapid diffusion of misinformation and poor individual knowledge resulted in the adoption of counterproductive disease prevention practices at both individual and collective levels. For instance, a resident in the U.S. died after consuming chloroquine (normally used to, e.g., clean aquariums) to cure COVID-19 based on inaccurate news about this 'cure' that had been disseminated through social media.

Conspiracy theories spread on social media have also been harmful by undermining public health messages [35,36].

6.3. The Learning Effect of Playing Together

Our study results suggested that the lack of a collective strategy based on knowledge has the potential to create self-defeating strategies, and new collective threats. However, we also found that playing was an effective and powerful learning tool. Participants repeatedly expressed their sense of gratitude and excitement because they learned both about technical aspects of the disease as well as interdependencies and collective action requirements. Our findings aligned with Tafesse et al. (2020), who found a need for learning approaches that support the diffusion of both technical disease aspects as well as giving attention to the existence of interdependencies and needs for collective action [37]. Given the feedback that we received from farmers, our method met those characteristics in that it let farmers actively experience their interdependence while also teaching them technical disease information. Hence, next to being an experimental tool, the Musa-game has potential as a learning tool that could be implemented by researchers and practitioners.

6.4. Implications for Communicating about Public Bad Problems

The Musa-game allowed us to explore the multidimensional causalities behind decision-making and their emergent outcomes. The mechanics of the game elicited farmers to learn and experience a complex reality in a simplified setting. Different forms of communication and deliberation opportunities (treatments) triggered players to make sense of their decisions and motivations at both individual and collective levels. These factors influenced decision-making and the outcomes in different communication treatments. Our findings suggested that collective (coordinated) actions are challenged by more than just social dilemmas. We found that, besides social dilemmas, players' coping capacity and risk perception shape the collective capability to organize the prevention and control of BXW in a coordinated way (Table 4). Those groups with the most opportunities to communicate performed better. Players reported learning from each other, jointly evaluating risks, and making agreements. Group communication hence appears critical, providing a space for deliberation and collective sense-making and creating conditions necessary to reach a consensus on a strategy and come to collective action.

Table 4. The three factors influencing collective action to prevent and control BXW disease in the Musa-game.

Social Dilemma	Players (farmers) face the dilemma of either taking a preventive/control action (investment) against BXW, which could potentially harm themselves and others. The dilemma, shaping actions, includes when (game-round) and where (location on the gameboard) to act.
Risk Perception	Players' perceived risk of disease infection and punishment (monitor) influences the decision about when and where to act.
Coping Capacity	Players' decisions to act (accurately and timely) are influenced by resource availability, especially capital, information, and knowledge.

Recent experimental findings by Cieslik et al. (2021), from Ethiopia, showed that a digital service can provide a platform for peer-to-peer communication that facilitates collective action and contributes to catalyzing development impacts, provided that farmers had a prior understanding of their interdependence [38]. In real-life, the power of peer-to-peer communication was shown in study results from Ghana, showing that social media groups aided rapid communication about the emerging fall-army-worm issue [39]. Yet, when we look at how digital services in agriculture are generally designed, we come to an interesting, yet concerning, conjecture. Supposed key benefits of digital agriculture services over traditional face-to-face services are that they improve access to timely and accurate information [27] and can be tailor-made for individual farmers and farms. As a result, services specifically built to support documenting and dissemination of information about agricultural problems are targeting individual decision-making [40,41]. Yet, in light of our findings and those by Damtew et al. (2020), which informed us that addressing complex agricultural problems demands collective sense-making and action to prevent them from becoming public bads, we observe an emerging issue [34]. Although we do agree that more targeted information provisioning to individuals may enhance timeliness and accuracy for single farmers, we believe that it may simultaneously reduce space for deliberation and collective decision-making. Focusing on the individual alone, without being informed about or strategizing with fellow farmers, reduces opportunities for collective sense-making. Our concern is that tailor-made advice given to individual farmers and the preceding actions may conflict with collective needs and that the sum of actions can result in worse collective performance towards the prevention of a public bad. Knowing about this potential negative impact of digitally mediated communication is relevant for projects like ICT4BXW and policymakers. Although more research is necessary, we advise that digital agriculture interventions targeting complex problems and public bad management consider the need for collective sense-making and deliberation either by protecting existing or creating new (digital) opportunities that foster tailor-made communication, but in a collective setting.

6.5. Outlook for Dynamic Socio-Ecologic Games

Considering our findings, we conclude that *dynamic socio-ecologic* games (DySE), like the Musa-game, can yield rich and insightful data. Using a board game, we were able to model a public bad risk as SES with its biophysical and institutional characteristics and could experiment with a social-dilemma regarding risk management using communication treatments. The presented social dilemma gave players a temporary shared experience, while the addition of a qualitative method, i.e., FGD, allowed respondents to make sense of their decisions and relate to real-life practices used to maintain livelihood resilience. This supports researchers in interpreting the meaning of the quantitative game data. Additionally, it appears that games like the Musa-game provide promising interactive learning tools. The ability to visualize human-human and human-non-human interactions and dependencies are particularly valuable for learning. To be conclusive about the effectiveness of DySE-games, experiments need to be conducted at scale. With a larger sample, the test-findings and hypotheses presented in this article could be verified. Secondly, with a larger sample more in-depth analyses, e.g., comparing data from different age and gender groups or different geographic locations, would become possible. Studying the influence of age and gender on communication behavior, decision-making, individual and collective performance is especially interesting given that, for example, women have historically had less access to information and knowledge. While this exclusion of women has so far been mostly addressed as an individual issue, the DySE-games may shed a different light on this. Last, we recommend further research on the interplay between real-life experiences and practices of farmers, the decisions they take while playing, and the basis on which those decisions are made. For future applications, opportunities for digitizing DySE-games could be explored. A digital version would simplify game implementation and create a more controlled experimental environment, thus reducing error chances. A digital game would also provide more options for visualization and collective sense-making within the game environment. The level of digital literacy of players may be a barrier, however, and hence needs to be assessed and considered beforehand.

Supplementary Materials: The following are available online at https://github.com/joangavi/MusaAnalyticalTool, since 21 June 2021, Software (codes). The following are available online at https://www.mdpi.com/article/10.3390/su13169353/s1: MusaAnalyticalTool_v5.0.rar, MusaGame_Rwanda_Kayonza_full_dataset.xlsx, Imput_information_guideline_MusaTool.txt.

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Institutional Review Board (or Ethics Committee) of Wageningen University and Research (protocol code Netherlands Code of Conduct for Research Integrity 2018 and approved on 1 April 2020).

Informed Consent Statement: All subjects gave their informed consent for inclusion before they participated in the study.

Data Availability Statement: The data presented was generated during the study and it is available in supplementary material of this article.

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Conflicts of Interest: The authors declare no conflict of interest. This paper is intended to disseminate research and practices about the production and utilization of roots, tubers and bananas and to encourage debate and an exchange of ideas. The views expressed in the paper are those of the authors and do not necessarily reflect the official position of RTB, CGIAR or the publishing institution.

Appendix A

Table A1. SES framework adapted to BXW disease in Rwanda.

Components	Description and Example	BXW Context
Agricultural livelihood system (ALS)	This is represented by a specific territory where diverse agricultural livelihood activities take place, involving crops, animal husbandry, and related activities and assets that provide ecosystem services to farmers and consumers.	Banana small scale farming for consumption and market.
Livelihood unit (LU)	This is a specific agricultural activity providing ecosystems services needed to make a living, e.g., cattle for milk and meat, rice production for human consumption, maize production for human or animal feed.	Banana as food and source of income.
Livelihood assets	Human: peoples' health and ability to work, knowledge, skills, experience; Natural: land, water, the forest, livestock; Social: trust, mutual support, reciprocity, ties of social obligations; Physical: tools and equipment, infrastructure, market facilities, water supply, health facilities; Financial: conversion of production into cash, formal or informal credit.	Banana production contributes approximately 50% of the diet of 32% of the households in Rwanda [42]. Therefore, declines in production impact household income as well as food and nutrition security, and social and cultural wellbeing [19].

Table A1. *Cont.*

Components	Description and Example	BXW Context
Public bad risk context (PBRC)	Conditions of vulnerability and characteristics of the hazard that hinder or limit the probability of a public bad.	BXW can result in yield losses up to 100%. No cure exists for BXW. Once the pathogen establishes, the stem will inevitably die. Eradication of BXW is considered impossible, but outbreaks can be managed with preventative and early response agricultural practices. Collective-coordinated actions are needed, as farmers' production activities and outcomes are interconnected.
Vulnerability	The vulnerability (of any system) is a function of three elements: exposure to hazard, sensitivity to that hazard, and the capacity of the system to cope, adapt, or recover from the effect of those conditions [43].	Farmers lose their income and food security (loss of livelihood), especially for cooking banana because this one is the crop that provides a stable income. Exposure is related to agroecological conditions. In higher lands, there is less exposure because there are fewer vector insects, also the variety. The capacity to cope/adapt/recover is limited and mostly dependant on the wealth of the farmers and their ability to access off-farm income opportunities. More wealthy farmers have more access to information, and female farmers are more isolated from advice/information/resources (they are more vulnerable).
Hazard	A physical event, phenomenon, or human activity that has the potential to cause the loss of life or injuries, property damage, social and economic disruption, or environmental degradation. Its potential can be characterized by its probability (frequency) and intensity (magnitude or severity) [44]	BXW, caused by the bacterium Xanthomonas campestris pv. Musacearum, endangers the livelihoods of millions of farmers in East and Central Africa [42,45] and can result in yield losses up to 100%. BXW is highly transmissible and can spread rapidly through infected plant material, cutting tools, long-distance trade, and vectors such as birds, bats, and insects [17].
Risk perception	Risk perceptions are formed by common-sense reasoning, personal experiences, social communication, and cultural traditions. These are the contextual aspects that individuals consider when deciding whether or not to take a risk and selecting reduction or preventive measures [31,46].	Beliefs about BXW: some farmers compare it to HIV or apocalypse, and therefore they think it cannot be controlled. Uncertainty: farmers feel they are not in control, and therefore if the plant gets infected, uprooted and then re-planted, it is just to lose it again. Beliefs about the system: farmers know they might be forced to uproot if the plantation is infected, and therefore, they try to hide it. Believes about neighbors: Farmers see a risk in their neighbors' disease management practices. If the farmer tries to control the disease, but the neighbors do not, they will get the disease anyway.

Table A1. *Cont.*

Components	Description and Example	BXW Context
Risk governance system (RGS)	Rules (operational, collective-choice rules, constitutionals), property right regimes (private, public, common, mixed), network structure (centralized, non-centralized) [31].	Rwanda's current policy for BXW disease outbreaks prescribes a practice called Complete Mat Uprooting (CMU). It involves uprooting the diseased stem and all lateral stems and shoots (i.e., the entire banana mat) regardless of their infection status. All uprooted material should be buried and covered with soil. Uprooting takes place in an early disease stage to reduce the chances of further disease transmission. In high incidence cases (>70% of the banana mats showing symptoms), the whole plantation must be uprooted [18]. Given its impact on livelihoods, farmers are reluctant to comply, hiding the disease by cutting down symptomatic stems or leaves to avoid enforced uprooting.
Direct users	Farmers and households that depend on the livelihood unit.	Banana farmers
Collective action problems	Coordination of responses to problems among direct users triggered by social dilemmas, risk perception, or coping capacities.	Increasing exposure to the disease is related to farmers preventive and responding measures because the spreading mechanisms and management strategies interconnect them (cutting flower, disinfecting tools, etc.) socially, ecologically, and geographically.
Action Interactions (I) and outcomes (O)	Action situations are where all the action takes place as inputs are transformed by the actions of multiple actors into outcomes [47].	Plant, pathogen, transmission mechanisms, and different actors' cultural practices interact to create the conditions for BXW spread.
Social, economic, ecological, environmental, and political conditions (SEC)	Economic development, demographic trends, political stability, government (settlement) policies, market incentives, media organizations, the biophysical environment and climatic conditions.	The Rwanda Agriculture and Animal Resources Board (RAB) is responsible for disease prevention, control, monitoring and responding to outbreaks. They work through the different layers of the country's extension system, reaching down to the level of villages where 'farmer promoters' act as elected village extension agents.
Related socio-ecological systems (ECO)	Other livelihood systems interlinked to the one in question.	No other linked systems were included in this study.
Dashed arrows	These denote feedback from action situations [47].	NA
Dotted-and-dashed lines	These surround the focal SES and are influenced by exogenous factors, which might emerge from dynamic processes at larger or smaller scales, either inside or outside the focal SES [47].	NA

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