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Qualitative Causal Loop Diagram: One Health Model Conceptualizing Brucellosis in Jordan

Haitham Taha [1,*], Jo Durham [2], Carl Smith [3] and Simon Reid [1]

[1] School of Public Health, The University of Queensland, Herston, 4006 QLD, Australia
[2] School of Public Health and Social Work, The Queensland University of Technology, Kelvin Grove, 4059 QLD, Australia; joanne.durham@qut.edu.au
[3] School of Business, The University of Queensland, St. Lucia, 4072 QLD, Australia
* Correspondence: h.taha@uq.net.au

Abstract: Background: Brucellosis is a serious public health problem distributed worldwide. Jordan has one of the highest incidences of brucellosis globally, mostly caused by infection with *Brucella melitensis*, which is associated with small, ruminant animals such as sheep. Sheep are an important livestock species in Jordan where there is a high value is placed on keeping animals at home. The incidence of human brucellosis rapidly increased following the Syrian conflict, in association with the resettlement of displaced people. Methods: A systems thinking (ST) approach was applied to develop a model to explain the dynamics of brucellosis in Jordan. A causal loop diagram (CLD) was developed to visualize and conceptualize interactions and feedback between several factors involved in sheep husbandry, animal and human health, and livestock trading systems. The CLD was constructed using information from published literature, historical governmental reports, policy documents and media coverage regarding brucellosis in Jordan. Semi-structured, in-depth interviews with diverse stakeholders were conducted to elicit information on their understanding of critical factors associated with brucellosis. Results: The CLD demonstrated that brucellosis transmission in Jordan is driven by sheep husbandry practices like livestock movement/trading and the management of symptomatic animals (those suffering abortion). Five dimensions were identified to be associated with brucellosis transmission: human infection; consumers; traders and markets; and livestock infection and control. Conclusion: The development of a CLD to explain brucellosis transmission in Jordan provides a better understanding of and reveals the multi-sectoral nature of the problem. The need for a multi-sectoral approach for effective brucellosis management in Jordan is clear from the five dimensions identified.

Keywords: brucellosis; system dynamics modelling; systems thinking; causal loop diagrams; CLD; system dynamics modelling; one health; model; mapping; feedback loops; epidemiology

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1. Introduction

Brucellosis is an acute febrile illness of humans and animals caused by infection with different species of the bacterium *Brucella. Brucella* infection in humans is associated with direct or indirect exposure to infected animals or through the consumption of uncooked meat or dairy products [1,2]. Brucellosis caused by infection with *B. melitensis* is associated with the most severe disease course and highest human burden [3]. Brucellosis is considered a neglected zoonosis by the World Health Organisation (WHO) because it is not considered a priority disease in most countries and is, therefore, underreported [4].

Brucellosis is endemic in many countries, particularly Middle Eastern countries, which have the highest incidence of human cases globally [2,5]. Recent studies in Jordan suggest the incidence of human brucellosis is increasing, with consumption of dairy products and direct contact considered the main risk factors [6]. In addition, a recent study demonstrated that the prevalence of *Brucella* infection in small ruminants in Jordan was 34% (95% CI: 28–40) [7].

The livestock sector accounts for around 55% of the agricultural sector in Jordan [8], and it is an essential sector for Jordan's food security through the production of meat and milk [8]. Animal husbandry in Jordan largely operates as a smallholder-based traditional husbandry system that is characterised by relatively unsophisticated low-input animal management practices. Currently, there are around 30 thousand smallholders in Jordan, who mostly possess small numbers of sheep [9].

Previous studies on brucellosis in Jordan and the Middle East have identified risk factors [10,11] without providing information on the underlying drivers of that explain the transmission dynamics. For example, husbandry practices such as lending rams, close contact, and abortions among sheep were identified as the major source of *Brucella* transmission in livestock and humans [7]. However, in isolation, these factors do not enable an understanding of the major interactions between sectors that explain the brucellosis dynamics over time.

Systems thinking, including system dynamics modelling, has been used in several different fields to help decision-makers understand and predict the dynamic behaviour of complex systems that have been applied to aid decision-making for some complex environmental health problems [12]. It is a particularly useful approach for the study of zoonotic diseases, such as brucellosis, which involve multiple animal species, multiple sectors, and a number of key cultural and economic drivers. Systems thinking thus aims to enable researchers to gain insights into the whole system as a result of being able to view the relationships, interactions, processes, and feedbacks between the elements that constitute the whole system [13]. It is a principally valuable method to resolve real-world problems when is not possible to apply experiments or when there are ethical or realistic restrains [14,15].

This study was the first part of a two-part study to develop a quantitative system dynamics simulation model. This paper describes the elicitation of the mental models of key stakeholders as regards brucellosis in Jordan, which were used to construct a causal loop diagram that is a conceptual model of the system components and their inter-relationships. Key stakeholders are the parties that have an interest in, are involved in, affect, or are affected by [5] the brucellosis transmission system in Jordan.

2. Materials and Methods

2.1. Qualitative Data Materials

To develop the conceptual model, the following data and information sources were used:

1. Publicly available data sets of reported human brucellosis cases (incidence and prevalence) in Jordan between 2004 and 2022 from the Jordan Ministry of Health (MoH) website [16].
2. Annual agricultural reports published by the Ministry of Agriculture (MoA). Data included prevalence of *B. melitensis* in sheep, sheep vaccination levels, and sheep numbers between 2004 and 2022 [8].
3. Publicly available data sets from the Jordan Department of Statistics. Obtained data include population numbers in Jordan, sheep farmer numbers, and sheep numbers in Jordan between 2004 and 2022 [17].
4. Other publicly available local or global reports by other local, regional or international media and news reports such as Food and Agricultural Organization (FAO) reports, the World Organisation for Animal Health (WOAH), and the World Health Organisation (WHO).
5. Published academic literature and policy documents.

In addition to the qualitative data materials, a stakeholder identification and semi-structured interviews were conducted to enrich the conceptual understanding of brucellosis transmission system in Jordan and build the qualitative model.

2.2. The Stakeholder Identification (Stakeholder Analysis)

Stakeholders were identified using the systematic approach proposed by Elias et al. [18] and the WHO's stakeholder analysis guidelines [16] to develop a map of key stakeholders who inform and provide new inputs to understand the brucellosis system in Jordan. Based on Elias et al. [18], systematic stakeholder identification for this research involved the subsequent steps:

1. Create a stakeholder map of the brucellosis system in Jordan.
2. Prepare a chart of specific stakeholders in this system.
3. Identify the stakes of stakeholders.

Key stakeholders were identified by listing and defining all possible eligible stakeholders involved and interested in the brucellosis system in Jordan, whether affecting or affected by the brucellosis system. Potential stakeholders from different geographical areas and administrative positions were considered. The listed stakeholders were prioritized by a local governmental expert—who knows the sector, the policy, and the stakeholders—to refine and prioritized a shortlist of stakeholders for further consideration.

Each stakeholder's information and characteristics were explored, identified, and recorded. The information included stakeholder's position, organisation, ability to affect the system, knowledge, and interests. The obtained data from this stage was integrated and used to inform and conduct the semi-structured interviews. Figure 1 presents a summary of the process of stakeholder identification.

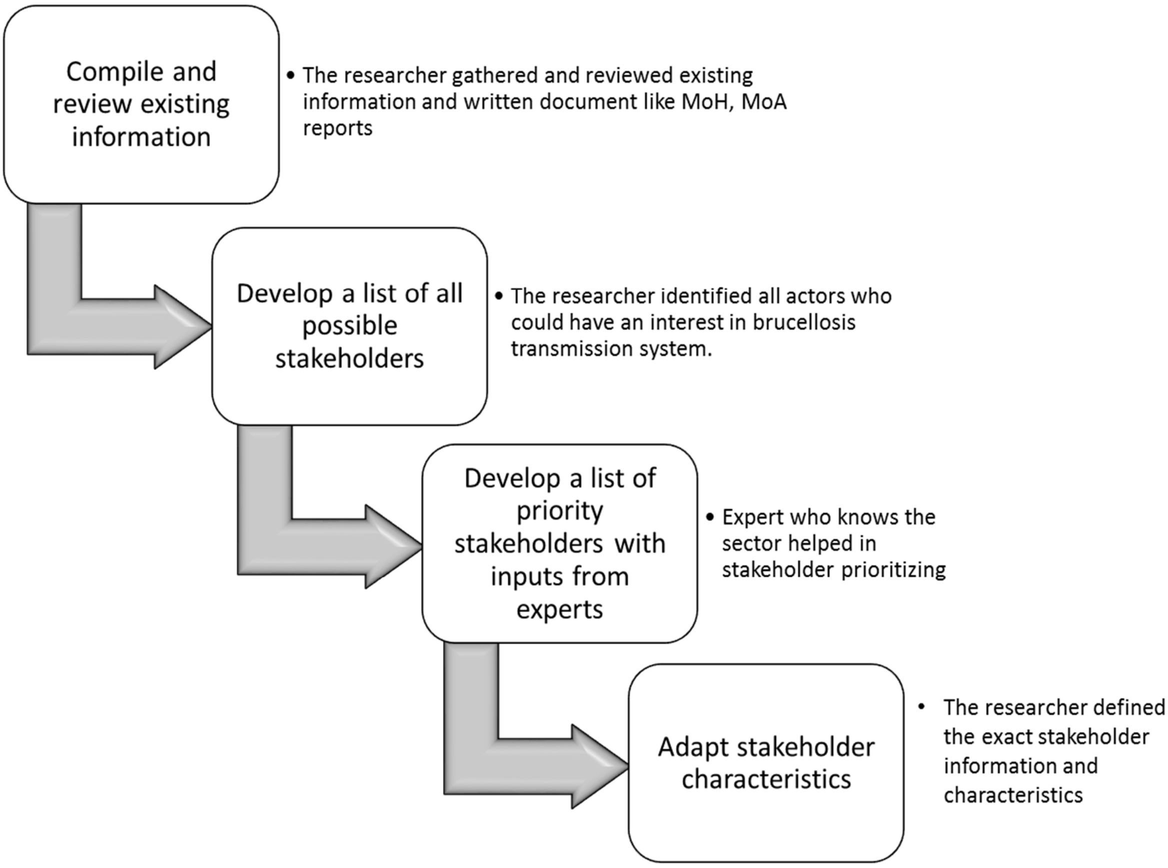

Figure 1. Stakeholder identification process.

2.3. Semi-Structured Interviews and Causal Loop Diagram Development

2.3.1. Sample Selection and Sample Size

A purposive and snowball sampling was conducted to recruit participants who were likely to know about brucellosis or sheep husbandry and trade in Jordan [19]. A field facilitator assisted with the recruitment of participants. Attempts were made to recruit 18 participants comprising 3 from each of the 6 stakeholder groups. The final total number of participants was 14. The following Table 1 presents the stakeholders' list.

Table 1. Participants' group, positions, and organisations.

Group	Position	Organization
Health managers at JMoA governorates/directorates	Director of the veterinary health department	MoA
	Head of animal health division	MoA
Veterinarians at Jordan Ministry of Agriculture (JMoA).	Animal Health Department	MoA
	Microbiology Lab	MoA
	Head of quarantine division	MoA
Health managers at MoH governorates/directorates	Medical Doctor at MoH	MoH
	Head of disease monitoring and Surveillance department	MoH
Fellow university researchers who worked in a similar field area	Senior Disease Control Specialist	EMPHNET
	Academic Professor	University
	Postdoctoral Researcher	University
Local livestock farm owners	Sheep and Livestock owner	Smallholder
	Sheep and Livestock owner	Smallholder
	Sheep and Livestock owner	Smallholder
One Health Committee	Head of quarantine division	MoA

MoA: Ministry of Agriculture, MoH: Ministry of Health, EMPHNET: Eastern Mediterranean Public Health Network.

2.3.2. The Semi-Structured Interviews

Semi-structured interviews were conducted to collect qualitative data and develop the qualitative causal loop diagram and model. A question guide was developed (Table A1) with a series of questions to encourage detailed discussions to obtain better insights and understanding of each stakeholder's perspective and role in the system.

Ethical clearance was obtained to conduct the interviews. Additionally, a written participant information sheet and written informed consent were obtained before the interview. Interviews lasted 30–45 min and were audio-recorded with permission. Interviews were conducted face to face and, where possible, in English. However, most of the interviewees preferred to be interviewed in Arabic.

A conceptual map that represents a preliminary understanding of the brucellosis system, deduced by the researcher from the available literature, was prepared in advance and provided in hard copy to each participant. The map served two purposes: first, to be modified by the participants based on their understanding of the system; and second, to elicit further discussion to increase information gain and data saturation. Each participant's map modifications were documented as an audio and hard-copy record. These records were later used to aid the development of the qualitative causal loop diagram (CLD), model. This allowed for better data validity and thorough depictions of the participants' inputs and understanding.

2.3.3. Qualitative Data Analysis Process and Causal Loop Modelling

Data were extracted and analysed using the approach proposed by Halcomb et al. (2006) [20], as summarized in Table 2.

Table 2. A summary of data extraction method by Halcomb and Davidson used in the study.

Scheme	Description
1	Audio taping of the interview and concurrent notetaking
2	Reflective journaling immediately post-interview
3	Listening to the audiotape and amending/revision of field notes and observation
4	Preliminary content analysis
5	Secondary content analysis
6	Thematic analysis

An iterative process was used to extract data from each recording and the development of the CLD as summarised in Figure 2. The following sections present the details of the qualitative data analysis process used to develop the qualitative CLD and model.

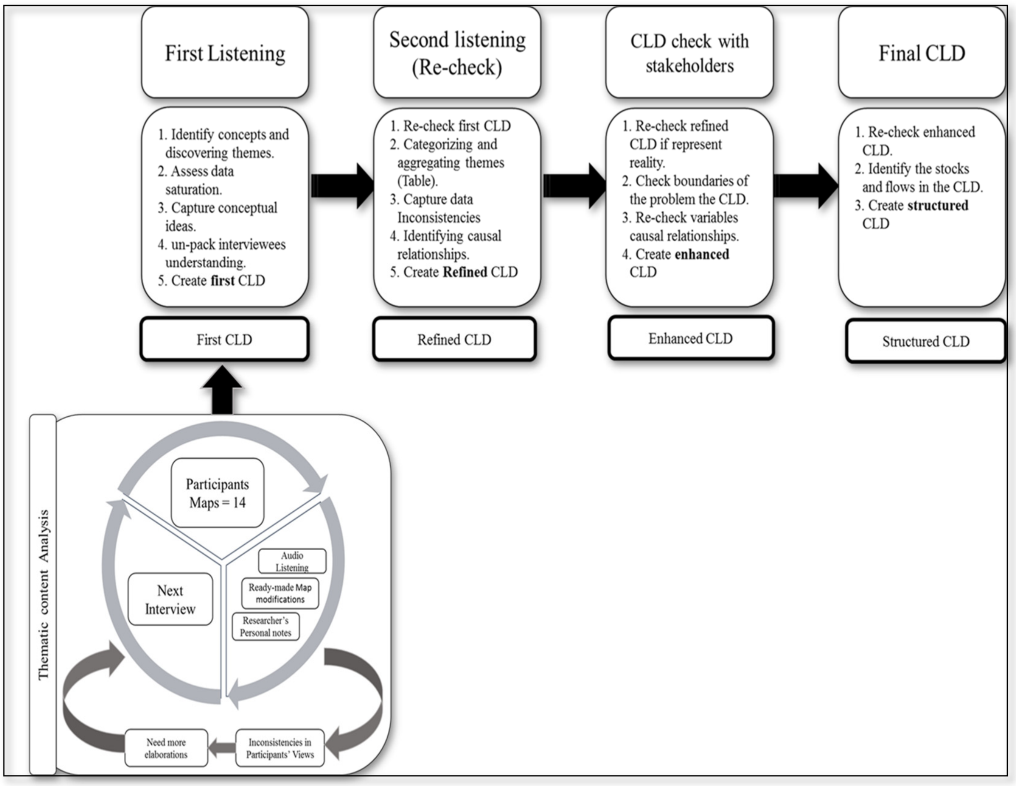

Figure 2. Overall qualitative data analysis process and CLD building.

2.4. *First Review of Interview Transcripts and Recordings*

Qualitative data analysis was initiated through progressive listening to all fourteen audio-recorded interviews to explore the available data, identify concepts, discover themes, capture preliminary ideas and relationships, and unpack and depict each participant's understanding for the research project (transmission of *Brucella* in Jordan) [20,21]. This created a preliminary conceptual CLD for each interviewee, representing a portrayal of the problem's extent and drawing its boundaries.

The preliminary conceptual map for each participant was created using Stella Architect (Version 1.9.1 iSee Systems) [22], into which all relevant data extracted from the interview was transferred and saved using the participant's code identifier. Additionally, each participant's map was updated using the feedback, modifications, and suggestions made on the ready-made conceptual map (hard copy) that was presented to them at the end of the interview (the participants were allowed to modify the conceptual map based on their knowledge on the research project). This allowed us to capture feedback and ideas and to record the proposed modification of the map structure along with any other suggestions.

A thematic content analysis was also conducted to analyse the data and to create refined maps [22,23]. Qualitative data were condensed and grouped into less content-related category sets that might share the same meaning [23], and a valid and replicable interpretation from the data was constructed that offers new insights and knowledge of the reality and facts [24]. The product of the content analysis was the establishment of concepts that define the embedded feedback loops and interconnections in the brucellosis system in Jordan that were used to finalise the conceptual model [25]. Table A2 presents the thematic analysis and variables captured.

Maps generated through this process (14 maps) were collectively combined to compose one single first draft of the CLDs. Furthermore, the researcher's notes, insights, and ideas in the interviews were recorded and incorporated to produce the first draft of the CLD. Inconsistencies noted in participants' views were resolved by further elaboration requested from the participants, which created additional inputs into the CLD [21]. Data saturation was confirmed when no new information was added to the map [26].

This stage produced the first draft of CLDs of the drivers of brucellosis in Jordan.

2.5. Second Review of Interview Recordings: Re-Checking

Once the first CLD was created, audio recordings from the interviews were reviewed a second time to check that the first draft of the CLD captured all topics and ideas mentioned by participants. This enabled inspection and re-examining of the identified variables and their corresponding themes captured in the first listening stage. These variables were further grouped and categorised to produce a table showing the captured link between the variables (themes) and brucellosis, Table A2. The output of this process was a revised and better representation of the relationships embedded in the CLD, enhancing the CLD conceptualisation and documenting (for reference) the relationships between captured variables and their representation in the CLD. Finally, data saturation was re-checked again. This stage produced a refined copy of the CLD.

2.6. Third Review: Review of CLDs with Key Stakeholders

Online video meetings (5 in total) were conducted with key stakeholders using Skype to check if the refined CLD represented the brucellosis system in Jordan [13]. This stage created an enhanced CLD. The following Table 3 presents the experts' positions and affiliations.

Table 3. Expert stakeholders involved in the review and finalisation of causal loop diagrams for the brucellosis system in Jordan.

Position	Affiliation	Number
Head of quarantine division and member of one health committee	Ministry of Agriculture	1
Head of animal health division and member of one health committee	Ministry of Agriculture	1
Senior disease control specialists	Eastern Mediterranean public health network (EMPHNET)	1
Director head of the animal health division	Ministry of Agriculture	2
Total		**5**

The refined CLD was shared with each stakeholder by e-mail before each meeting. Meetings lasted an hour and involved a collaborative review of the refined CLD boundaries and included causal relationships [13]. Changes proposed by each stakeholder were recorded on an individual copy of the CLD and saved in Stella Architect. Following the individual meetings, a conference Skype video-call (group meeting) with all stakeholders was conducted to resolve inconsistencies that emerged during the previous individual meetings. This created an opportunity for stakeholders to review the CLD as a whole and develop a consensus on the structure of the CLD.

2.7. The Final Causal Loop Diagrams

The enhanced CLD was used to generate the structured CLD that is needed for developing a quantitative simulation model. A structured CLD is a causal loop diagram that holds all the information needed, like the polarity and the direction, to transform the qualitative map into a quantitative model using the CLD by identifying the stock and flow variables in the CLD that will be used in the quantitative model [27].

2.8. Data Management

All personal identifiers of the participants were removed and re-coded. The coded identifier of the participants was saved and kept in a safe directory under the supervision of the researcher. The data, as voice recordings and transcripts, were stored in the University of Queensland Research Data Manager (UQRDM) system. Two copies of the data, the original (raw data) and the processed data (clean organized data), were stored.

3. Results

3.1. Problem Identification

The emerged qualitative themes were classified into five main dimensions: human infection, consumers, trades and markets, sheep infection, and control. The features and problems of each dimension that were articulated by stakeholders are summarised in Table 4.

Table 4. Problem articulation dimensions, related features, and identified problems.

Problem Dimension	Features	Identified Problems
Human Infection	Reporting, diagnosis, endemicity, surveillance, notification	Weak reporting and diagnosis, tolerability of endemic status
Consumers (Community)	Hygienic practices, food safety, contact measures and safety	Awareness, education, traditional values, cultural views, the micro-economic financial support system
Trade and Markets	Local markets, individual trade prices, production system	Weak veterinary supervision, unregulated trade, fragmented markets, price change, black markets, gov. feed support, sheep individual ownership
Sheep Infection	Mixing and movement, reporting, diagnosis, surveillance, notification	Weak reporting and diagnostics, uncontrolled movement and mixing between herds
Control	Vaccination, regulations implementation, capacity building, budget, reachability	Vaccination strategy and low rates, farmers' awareness, lack of regulations or implementation, loss of motive for implementation, low budget

The main thematic area related to brucellosis is the husbandry practices associated with the breeding and movement of sheep. Other themes included food safety, control measures, and farmers' awareness of brucellosis.

Husbandry practices (management of aborted animals and livestock movement and mixing) in local trade markets are the **main themes** involved in brucellosis transmission dynamics. Additionally, food safety (cheese processing and consumption), control measure (diagnosis, testing, reporting, vaccination, quarantine, and surveillance programs), and farmers' occupational hygiene and safety through health education programs are important themes to highlight. Other themes include geographical locations and seasonal factors.

We identified the **major stakeholders involved** in brucellosis transmission. The major identified stakeholders are the Ministry of Health, Ministry of Agriculture, farmers' association, non-governmental organizations, and the consumers.

Loss of coordination is a major weakness of both the MoH and MoA. The MoH's strengths lie in properly diagnosing and reporting human cases; however, they have weak coordination and reporting with the MoA. We found the MoA to be the main provider for veterinary services, control programs, and animal surveillance; however, they operate under a low budget, and have a weak implementation of laws and coordination with the MoH. The farmers are the main link between the MoH and MoA and provide a useful link to the system structure and behaviour; however, they have a weak role because they are peripheral on policy designs and are difficultly managed. The non-governmental organisations (NGOs) are independent of the governmental structure in Jordan and, therefore, have independently structured aims for brucellosis control and significantly support brucellosis control efforts such as awareness programs. However, NGOs have no official involvement in the national government plans and policies and, therefore, have a weak authority over management and brucellosis control plans. Finally, the consumers represent the focal point that links human and animal sectors. However, consumers infected with brucellosis are often not recognised and difficult to track, and furthermore, consumers are an unstructured group of people, their consumption behaviours corresponding to traditional and cultural values.

Five main brucellosis transmission **dimensions** have emerged. Human infection, consumers, trade and markets, sheep infection, and the control dimensions. The human infection dimension is characterised by weak case diagnosis, reporting, and tolerability of endemic status. The consumer dimension featured by the hygienic and food safety practices has low awareness and education levels due to the traditional and cultural attributes related to livestock, leading, therefore, to brucellosis infections. Additionally, microeconomic financial factors relate consumers to livestock sector, leading, therefore, to brucellosis transmission. The trade and markets dimension is represented by the local livestock trade, markets, and prices characterised by weak veterinary supervision, unregulated trade, fragmented individual markets, price change, black markets, and governmental feed support. The livestock infection dimension features uncontrolled livestock mixing and movement and has weak case reporting and diagnosis. Finally, the control dimension, characterised by vaccination, capacity, and budget, has low vaccination rates and coverage and low budgets and human resources.

Sub-system diagram

We presented the brucellosis transmission system dimensions as a sub-system (sectors) diagram to allow a better understanding of the system and give an overview of the conceptual system structure. The following Figure 3 presents the sub-systems involved in the structural framework of the brucellosis transmission system in Jordan.

Brucellosis infection in livestock (livestock infection sector) responds to variables within the livestock sector such as ownership and trade style. Similarly, the livestock sector (represented by the MoA) responds to the control sector (represented by the strategies and the policies) in the system. This, in turn, would influence the consumer and contact behaviours, consequently affecting the human infection sector, represented by the prevalence of human brucellosis. Additionally, the veterinary services sector mainly influences service delivery and service capacity, which is an integral part of any disease control policy. This sub-system diagram is useful and aids in the identification of the scope and boundaries of the system. However, the developed CLD has a better explicit description of the key feedback loops that control the behaviour of the brucellosis transmission system in Jordan.

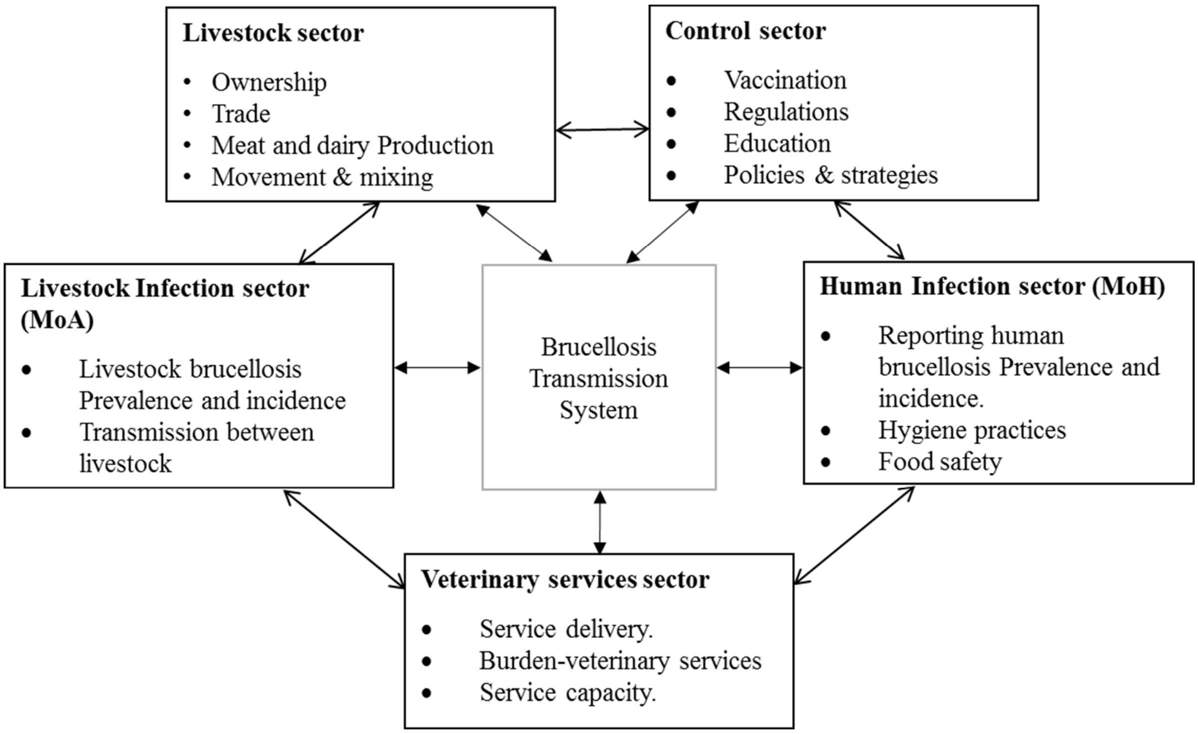

Figure 3. An overview of the model structure as represented by the sub-system diagram.

3.2. The Causal Loop Diagram

The CLD presented in Figure 4 represents a simplified combined representation of the system that shows the non-linear causal relationships that drive the dynamics of brucellosis in Jordan. Two re-enforcing causal loops and six balancing loops were identified in the CLDs. The resultant CLD has been categorised to represent five main sectors: sheep brucellosis (sheep), human brucellosis (human), health services, brucellosis control in sheep, the sheep trade and market, and veterinary services. Each of these sectors will be discussed in detail in the following section, discussion, to show its involvement in the whole brucellosis system. Trade and the market economic sectors are not presented because they were considered beyond the boundary and scope of the model, along with environmental aspects of brucellosis. The CLDs in the following section represent structured CLDs and show the non-linear causal relationships that drive the dynamics of brucellosis transmission in Jordan.

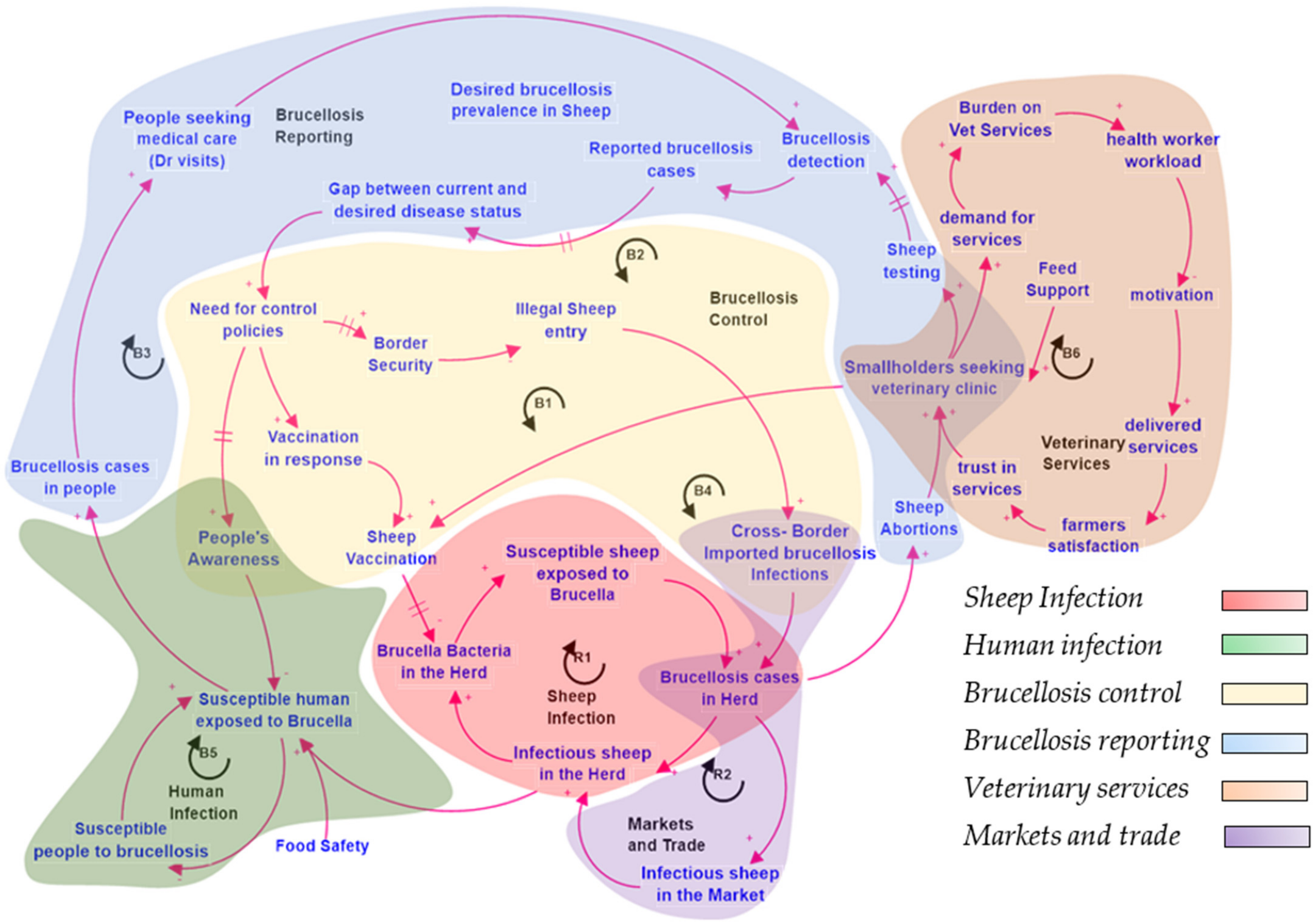

Figure 4. Combined CLDs of brucellosis dynamics in Jordan.

4. Discussion

The following section will discuss the emerged qualitative causal loop diagram presented in Figure 4; the discussion will be guided by the causal loop diagram specific for each identified sub-system it reflects.

4.1. Sheep-to-Sheep Brucellosis Transmission (Livestock Infection Sector) Loops R1 and R2

The central reinforcing feedback loop (R1) of brucellosis transmission in Jordan is the sheep (livestock) population, the core component of the dynamic hypothesis, Figure 5. The dynamic transmission of brucellosis among sheep exhibited reinforcing feedback behaviour (*behaviours or events inside the loop reinforce one another*). Therefore, the general behaviour of brucellosis transmission is explained: as more *Brucella* bacteria loads are circulating in the herd, the number of susceptible sheep exposed to *Brucella* increases through contact (direct or indirect), thus leading to increased brucellosis cases in the herd, which results in more *Brucella* bacteria in the herd, therefore reinforcing the effect [28].

Information from key stakeholders and several interviewees described the periodic sale of farm sheep through sheep markets; this means that an increase in brucellosis cases on-farm leads to an increase in the number of infectious sheep in the markets. Consequently, as other farmers buy sheep from the markets into their farms, this results eventually in increasing the number of infectious sheep in the herd at the farm (R2). The combined reinforcing natures of these two feedback loops are the main drivers of brucellosis transmission in Jordan.

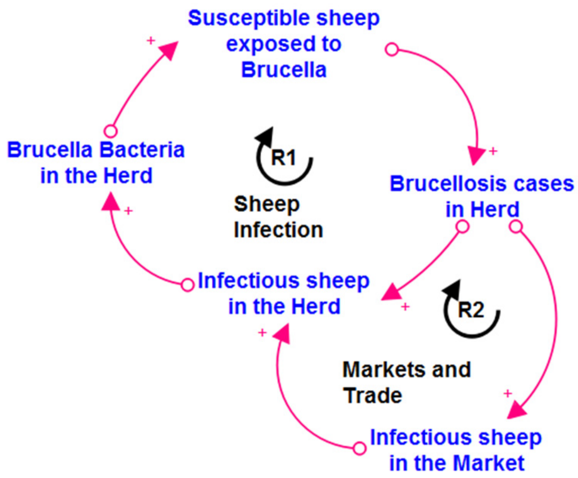

Figure 5. Brucellosis transmission in sheep population at the farm and the local markets. The positive sign (+) denotes that the source event/action affects the destination event/action in the same direction.

4.2. Sheep-to-People Brucellosis Transmission—Loop B5

The second component of the dynamic hypothesis in brucellosis transmission is the sheep-to-person transmission loop (B5). This simple loop exhibits a balancing feedback behaviour (*behaviours or events inside the loop counteract one another*) as it is assumed that once brucellosis infects people for the first time—through contact or consumption of unsafe dairy products [29]—immunity against brucellosis will develop and no re-infections could take place for the population who have been previously infected with brucellosis [30,31]. Therefore, as the number of "***susceptible people to brucellosis***" increases, the "susceptible human exposed to *Brucella*" increases, consequently reducing the number of the "***susceptible people to brucellosis***" and creating a balancing feedback behaviour. The following Figure 6 represents the balancing feedback loop of the brucellosis human infection dynamics.

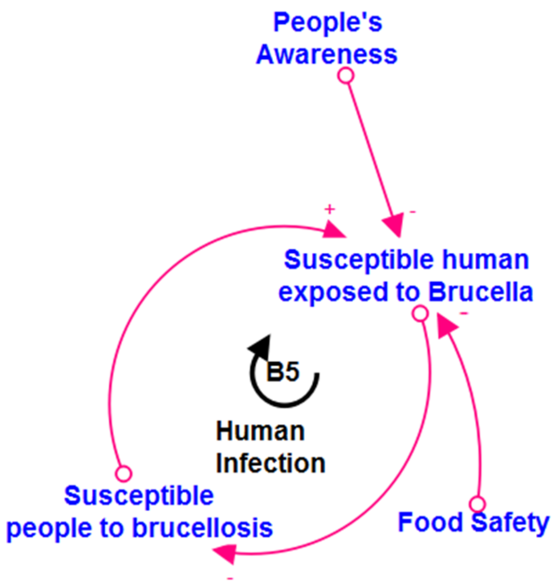

Figure 6. The balancing loop of human infection dynamics. The negative sign (-) denotes that the source event/action affects the destination event/action with a counter-effect.

4.3. Brucellosis Control Strategies in Jordan—Loops B1, B2, B3 and B4

Strategies to control brucellosis in Jordan are identified in a balancing feedback loop shown in Figure 7 as causal loops B1, B2, B3, and B4.

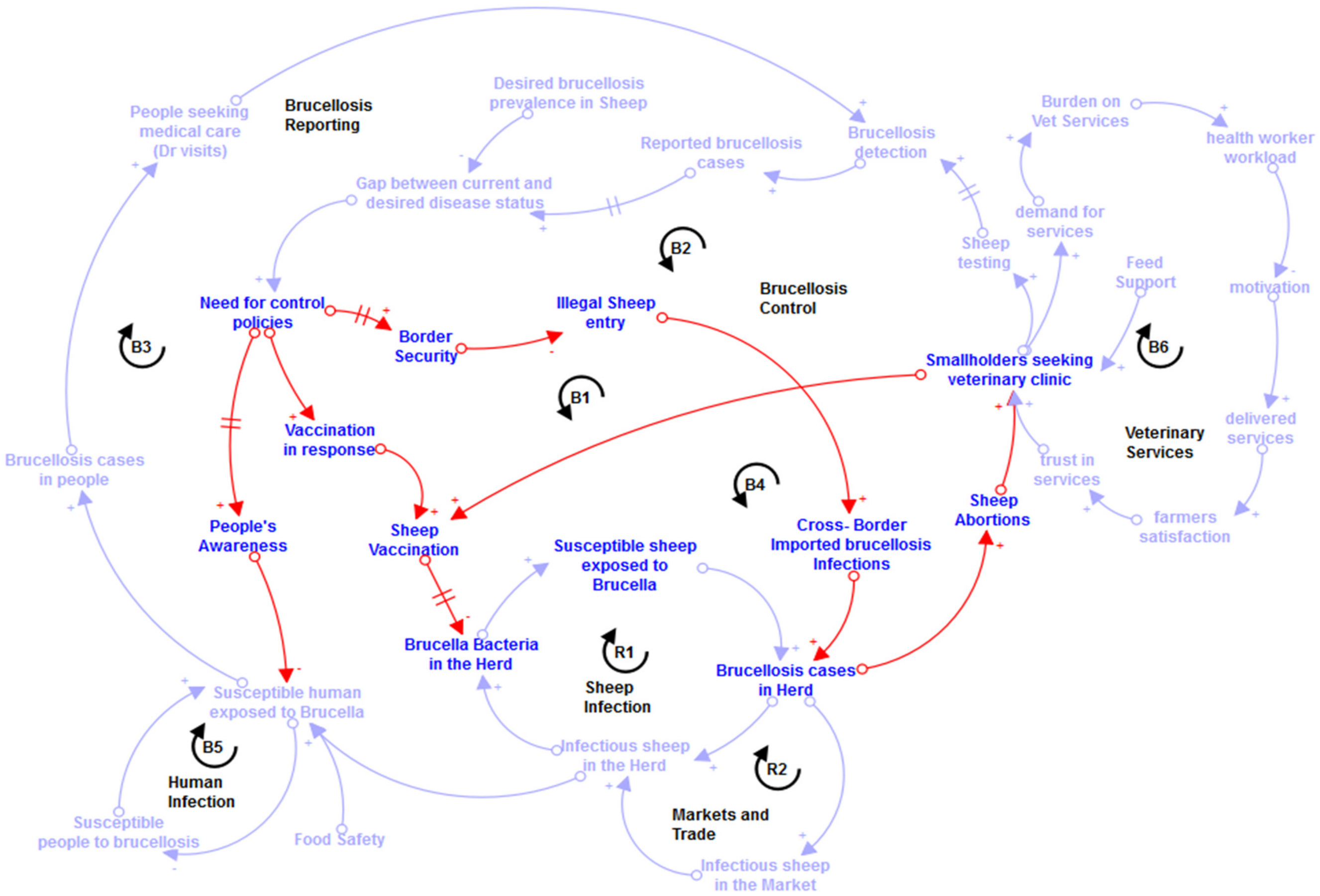

Figure 7. Balancing loops B1, B2, B3, and B4.

The current control strategy for brucellosis in Jordan as defined by stakeholders is regular annual sheep vaccinations against brucellosis [32,33]. This strategy usually depends on the smallholders requesting vaccination from the veterinary services via a visit to a veterinary clinic, principally in response to sheep abortions and to access feed support provided by the government. The balancing dynamics for the B4 loop are explained as follows: as the number of brucellosis cases in the herd increases, sheep abortions increase, eventually leading to increasing the frequency of smallholders seeking veterinary clinic and, therefore, sheep vaccination. Sheep vaccination reduces *Brucella* bacteria in the herd and eventually reduces sheep abortions. These dynamics have a delay represented by conducting the vaccinations and gaining immunity in sheep.

The balancing loop B1 exhibits a similar control strategy and is conducted whenever a brucellosis outbreak occurs. The balancing loop is explained as follows: to reduce economic losses due to abortion, smallholders seeking veterinary clinic behaviour increases, which increases brucellosis testing, detection, and reporting to create a gap between current and desired disease status. The desired disease status reflects the rate of brucellosis that veterinary services consider acceptable given the endemic status of the disease in Jordan [7]. Consequently, as the gap between the current and desired disease status increases, the need for control policies increases and leads the government to conduct additional vaccination programs in response to increase the rate of sheep vaccination (B1). These dynamics have several delays represented by testing, reporting, and control policy implementation (vaccination-in-response) delays.

Following the Syrian crisis in 2011, large numbers of sheep have been illegally transported into Jordan. Illegally imported sheep are used in the same way as local sheep, therefore increasing the risk of transmission because illegally imported sheep are unvaccinated and have a high prevalence of infection with *Brucella* [34]. Therefore, the balancing loop B2 represents a governmental strategy to control and lower the risk of brucellosis associated with illegal animal movement. The dynamics are as follows: as illegal sheep entry increases, the number of imported *Brucella* infections increases, which leads to an increase in the number of brucellosis cases in the herd. Therefore, an increase in border security measures will lead to a reduction in illegal sheep entry and eventually reduce the number of brucellosis cases from imported sheep (B2). These dynamics have several delays represented by testing, reporting, and control policy implementation (strengthening border security) delays.

The balancing loop B3 represents the control strategy for brucellosis designed to reduce brucellosis cases in people. This control strategy aims to raise people's awareness through education and awareness campaigns, particularly targeting farmers [35]. The balancing loop is explained as follows: the awareness programs increase people's awareness, which is assumed to decrease the number of susceptible humans exposed to *Brucella* and reduce the number of brucellosis cases in people (B3). These dynamics have several delays represented by reporting and control policy implementation (raising people's awareness) delays. These delays are important to identify because they are determinants of the speed of response and, therefore, brucellosis control. The following Figure 7 represents the balancing feedback loops B1, B2, B3, and B4 that control the dynamics of brucellosis transmission in Jordan.

4.4. Veterinary Services Demand in Jordan—Loop B6

The balancing loop B6 explains the role of a visit to the veterinary clinic in the system dynamics. The balancing loop is explained as follows: the increase in smallholders seeking veterinary clinics (representing visits) increases the demand for services, the burden on vet services, and the health workers' workload. This resulted in a decrease in the motivation, delivered services, farmers' satisfaction, and trust in services. Eventually, this leads to a decrease in smallholders seeking veterinary clinic and completes the balancing loop (B6). The following Figure 8 represents the balancing loop (B6) that contributes to brucellosis dynamics in Jordan.

4.5. Brucellosis Transmission is a Complex Problem

The feedback loops that drive the dynamics show the complexity of brucellosis transmission, as it involves many sectors in Jordan. The overall CLDs suggests most of the balancing feedback loops controlling brucellosis transmission involve at least two main sectors, the livestock (sheep) sector and the human infection sector. The balancing feedback loops are dynamic and loop across all other sectors to control brucellosis transmission. However, although stakeholders did identify brucellosis transmission as a complex and inter-sectoral problem, many stakeholders acknowledged the weak and deficient communication and collaboration between the different sectors involved. This dynamic and complex nature of brucellosis transmission across several sectors sheds light on the necessary collaboration between these several sectors to comprehensively control brucellosis transmission and close the gap between different sectors' responsibilities.

4.6. Delays in the Brucellosis Transmission System

Several delays have been identified in brucellosis transmission dynamic system. The delays could be material (related to human resources and testing capabilities) or informational (related to communication and information exchange) [15]. Material delays control the speed at which materials move in or out the stock, like testing collection and result speed; information delays concern the change of human beliefs and perceptions, like smallholder awareness [15]. These delays are important to identify because they play important roles in response speed and, therefore, brucellosis control. Numerous material delays have been identified in the sheep-to-sheep brucellosis transmission sector, including delays related to animal aging, losing immunity after vaccination, and moving from a healthy state to a diseased state. These delays are important as they control the speed of transmission of infection through venereal contact and vulnerability to brucellosis infection.

Other delays have been identified related to brucellosis control, like brucellosis detection, reporting, vaccination, and people's awareness. The importance of these delays is related to the amount of time needed and sufficient to create the gap between the desired and the current brucellosis status, encouraging and eliciting the government to respond through the controlling policies, which is an information delay within the system. Therefore, these delays are important to identify to achieve success in early interventions.

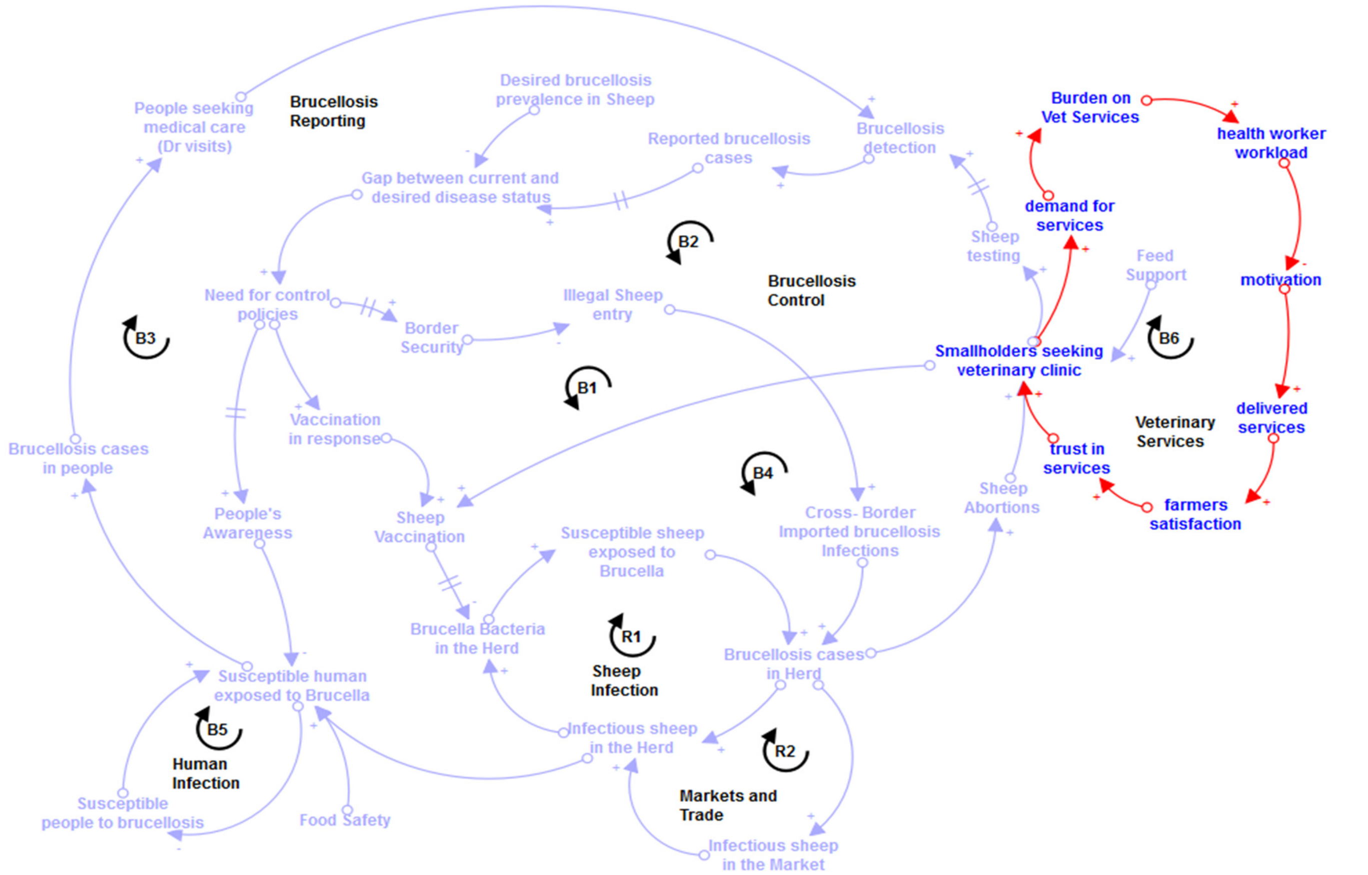

Figure 8. Veterinary services balancing loop (B6).

4.7. System Archetypes: Shifting the Burden Archetype

System archetypes are recurring system structures found in different situations, as each archetype has its distinctive behaviour over time that can be valuable for identification of its influence in the real world. Archetypes enable understanding of the leverage points in the system [15,36–38]. These archetypes can investigate the system behaviour and inform effective decision-making. The brucellosis transmission system archetype was identified during the CLDs' development.

The "*shifting the burden*" archetype represents the easy and quick problem solutions that are undertaken and favoured over the fundamental solutions through ignoring and delaying difficult fundamental solutions until the problem symptoms disappear [37,38]. The following Figure 9 represents the generic "*shifting the burden*" archetype. Problem symptoms are manifested and demands attention from the government; therefore, the fix (as a response) is usually quick and has a short-term effect that succeeds to remove problem symptoms, at least temporarily, to create a feeling of relief. However, the symptoms are expected to re-appear with a higher intensity [37,38].

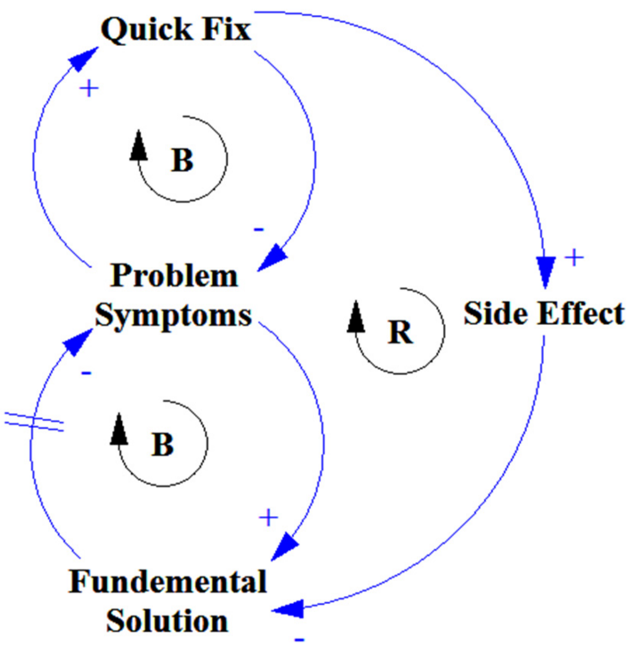

Figure 9. Generic "shifting the burden" archetype.

Similarly, in the case of brucellosis dynamics, government actions are directed towards the quick fix, regular annual sheep vaccinations, which is dependent on the current brucellosis prevalence (endemicity of brucellosis). Therefore, the key leverage point to the "shifting the burden" archetype in the context of this problem is to shift the strategy towards the sheep and sheep mixing, as the fundamental solution as it appears in Figure 10, and interrupt the reinforcing loops identified earlier (R1 and R2). This will reduce and slow the reinforcing infection loops affecting sheep mixing and *Brucella* transmission through the indirect and direct contact in the herd and market levels.

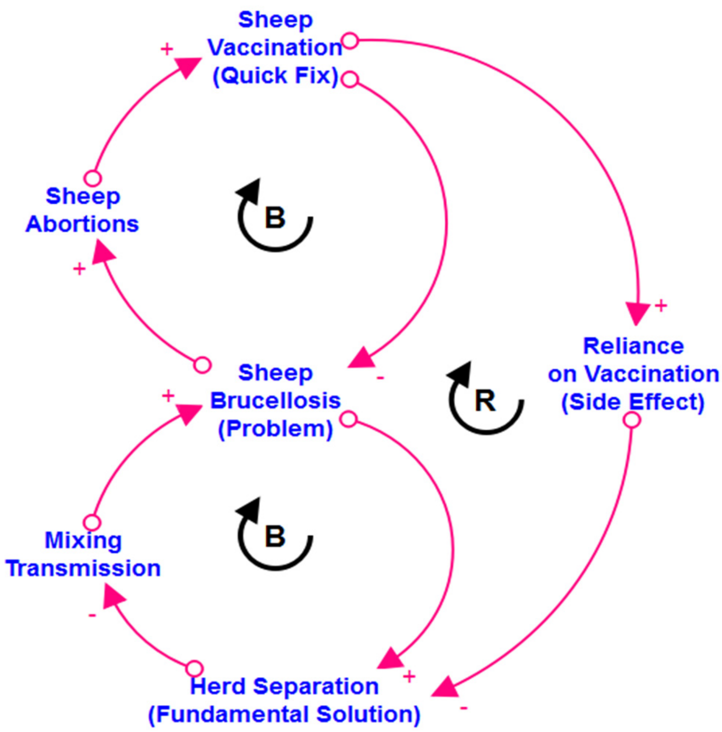

Figure 10. Brucellosis "shifting the burden" archetype.

In the case of brucellosis dynamics, infections among sheep are considered the "problem symptoms" and are characterised by sheep abortions. As sheep abortions increase and reaches a certain threshold, the government responds quickly via vaccination of sheep. Nonetheless, the threshold point that drives government actions and calls for a response is informal (there is no threshold set). Although vaccination increases sheep immunity, the vaccination strategy does not account for mixing, transmission among unvaccinated sheep, unsatisfactory vaccination rates, or coverage. Therefore, the transmission risks among unvaccinated sheep accumulate over time (delay), eventually increasing sheep infections, therefore leading to more abortions and disease transmission. Figure 10 represents the causal loop diagram of the "shifting the burden" archetype in the brucellosis system.

5. Conclusions

This study presented a CLD and mapping process that represents the systems thinking approach to conceptually portraying our understanding of the system structure that drives brucellosis transmission in Jordan. The factors involved in brucellosis transmission in Jordan are numerous; however, this study extends beyond listing factors, rather shedding light on the dynamic relationships driving brucellosis transmission and producing problematic system behaviour, unpacking the complex nature of brucellosis transmission in Jordan, and exploring the involvement of several sectors not currently involved; in particular, the role of the sheep market system (mixing) and managing infected sheep are two sectors not normally included in the management of brucellosis transmission in Jordan that were identified as significant drivers of the dynamics of brucellosis transmission in Jordan.

Through the mapping process, a better understanding of the problem was highlighted in the CLDs. The multi-sectoral nature of brucellosis transmission was revealed as the balancing and reinforcing feedback loops crossed several sectors in the conceptual system, which indicates the need for a multi-sectoral approach for the effective management of brucellosis transmission in Jordan. The complex and multi-sectoral nature of this problem was further manifested in that delays in one of the involved sectors might deteriorate the involvement of other sectors, consequently reinforcing brucellosis transmission. Furthermore, the tolerance level of brucellosis endemicity in Jordan is informal and inconsistent; this is assumed to regulate the speed of response to brucellosis transmission by the government. This lack of an evidence-based threshold of action typically compromises rapid and effective responses intended to control brucellosis transmission. Furthermore, the lack of coordination and communication between the MoA and the MoH, in addition to other sectors, amplified the response gap and led to disorganised management of the problem.

To our best knowledge, this study is the first to explore and show the complexity of the brucellosis transmission system in Jordan through the qualitative systems thinking approach. However, a few limitations were identified throughout the study. Although efforts were made to recruit a large number of participants, this study only included 14 participants; therefore, described factors and dynamics associated with the brucellosis transmission system that we found may not be fully representative for the situation. However, the participants were selected to represent each sector and category involved in the brucellosis transmission system. In addition, the causal loop diagram described in this study was developed based on a participatory process that interviewed stakeholders individually, lacking the group discussion element of the participatory process; therefore, it may not reflect or capture the understanding of all the aspects of the system. Hence, it reflects an interpretation of participants' interviews by the research team.

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Appendix A

Table A1. Question guide.

Themes of Question	Question	Prompts
1. Main Factors	What are the main factors that drive brucellosis?	Animals' factors: Brucellosis among sheep. How does it happen? Key factors: environmental health factors. Human factors. Hygienic husbandry practices. How they change brucellosis prevalence? Most important?
2. Main Stakeholders	Who are the main stakeholders?	How they are involved? How do these stakeholder groups interact? Roles in the infection system. Displaced population.
3. Sheep Markets	How are sheep markets organised between traders/smallholders?	Types: formal vs. informal. Informal markets: how it operates, how it is affected? Sources of informal sheep. Gov. feed support: consequences. When? Supply sources. Sources of sheep. Medically checked. Accessibility. Regulations. Informal slaughtering practices. Farmers' preferences: cooperation with informal markets. Reasons. Trade practices. Trade system: formal/informal. Traders' preferences. Impact of the displaced population? How does demand/supply dynamics affect the brucellosis system?
4. Sheep Prices	How are the sheep prices set?	How are prices set? How does it affect markets? Prices competition. What affects prices of sheep? How do changes in supply/demand affect the brucellosis system?

Table A1. *Cont.*

Themes of Question	Question	Prompts
5. Sheep Numbers	How do sheep supply sources affect sheep numbers?	What are the sources of other sources: external/informal supply sources
	How do sheep numbers affect sheep brucellosis?	Why? How? Factors that enable. Factors that disable. Mixing herds? How?
6. Changes in Brucellosis	What are the changes observed in brucellosis cases (human/animal)?	Past and now? What has changed? Main reasons for changes, main factors?
7. Brucellosis policies	How are the control policies implemented?	What should be done? How do control policies help control brucellosis?
8. Collaboration and communication	What level of collaboration and communication is there between different actors?	Who is involved? Barriers to collaboration? Enablers to collaboration?
9. Vaccination of Sheep	How does the sheep vaccination system operate?	Factors, government role, need to vaccinate, containment policies, how does it operate?
10. People's Awareness	What level of awareness is there of the increase in brucellosis? How does people's level of awareness of translate into practice?	Education, behaviours. Ingestion of infected foods. High-risk groups, behaviours. Changes in incidence? Geographic distribution?

Table A2. Qualitative data analysis (thematic content analysis) and the major identified themes.

Variable (Factors)	Theme 1	Theme 2	Theme 3	Theme 4	Effect
Traditional, cultural and religious beliefs	Awareness	N/A	N/A	N/A	Negative
Low level of farmers' knowledge about brucellosis	Awareness	Farmers beliefs	N/A	N/A	Negative
Low level of farmers' education about brucellosis	Awareness	Farmers education	N/A	N/A	Negative
Shared trust between smallholders	Awareness	Trust	N/A	N/A	Negative
Farmer-to-farmer influence	Awareness	N/A	N/A	N/A	Negative
Farmers' fear of quarantine	Awareness	Farmers	Reporting	N/A	Negative
Farmers' fear of cultural stigma (brucellosis)	Awareness	Farmers	Reporting	N/A	Negative
Poor socio-economic status of farmers	Awareness	Farmers	Education	N/A	Negative
Acceptance of brucellosis endemicity	Awareness	Human	N/A	N/A	Negative
Farmers' fear of vaccination	Control	Vaccination	Fear	N/A	Negative
Poor compliance of farmers to vaccination	Control	Vaccination	Farmers	Compliance	Negative

Table A2. *Cont.*

Variable (Factors)	Theme 1	Theme 2	Theme 3	Theme 4	Effect
Vaccine side effects (abortion)	Control	Vaccination	Side effects	N/A	Negative
Vaccination frequency	Control	Vaccination	Frequency	N/A	Positive
Vaccine efficiency	Control	Vaccination	Efficiency	N/A	Positive
Low vaccination rate	Control	Vaccination	Rate	N/A	Negative
Low vaccination coverage	Control	Vaccination	Coverage	N/A	Positive
Low control on livestock movement	Control	Movement	livestock	N/A	Negative
High vaccination burden	Control	Vaccination	Burden	N/A	Negative
Vaccination in response (female remaining stock)	Control	Vaccination	N/A	N/A	Positive
Good control of food safety	Control	Food Safety	N/A	N/A	Positive
Weak hygienic practices of slaughterhouses	Control	Human	Hygienic Practices	N/A	Negative
Low vaccination rate of Syrian livestock	Control	Vaccination	Syrian Crisis	N/A	Negative
Weak border security control	Control	Human	Border Security	N/A	Negative
High dependence on farmers to conduct the vaccination	Control	Vaccination	Human	Implementation	Negative
Weak supervision level over-vaccination process	Control	Vaccination	Human	Implementation	Negative
Low level of proper vaccination by farmers	Control	Vaccination	Human	Implementation	Negative
High corruption level	Control	Vaccination	Human	Implementation	Negative
Successful vaccination	Control	Vaccination	Human	Implementation	Positive
Vaccination based on the registration book	Control	Vaccination	livestock		Positive
Successful strategy	Control	Vaccination	N/A	N/A	Positive
Tendency to vaccinate	Control	Vaccination	N/A	N/A	Positive
High referral to university/private clinics	Control	Treatment	N/A	N/A	Positive
Vaccine availability	Control	Vaccination	Availability	N/A	Positive
Gov. medicine availability	Control	Vaccination	Availability	Free	Positive
Farmer high medicinal share	Control	Vaccination	Availability	N/A	Negative
Purchase medicine by farmers	Control	Vaccination	Availability	N/A	Negative

Table A2. *Cont.*

Variable (Factors)	Theme 1	Theme 2	Theme 3	Theme 4	Effect
Unregulated trade	Control	Regulation	Trade	N/A	Negative
Freedom of movement of livestock that aborted	Control	Regulation	Livestock	Husbandry Practices	Negative
Hygienic control measures on abortions	Control	Regulation	Control	Husbandry Practices	Positive
Implementation of biosafety measures in farms (not vaccine)	Control	Regulation	Farmers	N/A	Positive
Implementation of importation regulation	Control	Regulation	Trade	N/A	Positive
Wrong food handling tech	Control	Food Safety	N/A	N/A	Negative
Stakeholder collaboration	control	Information share	Collaboration	N/A	Positive
No involvement of farmers	Control	Information share	Collaboration	N/A	Negative
Informal communications between stakeholders	Control	Information share	N/A	N/A	Positive
Good response of vet services	Service delivery	Delivery	Veterinary	N/A	Positive
High service quality	Service delivery	Delivery	Veterinary	N/A	Positive
Insufficient number of trained health workers	Service delivery	N/A	N/A	N/A	Negative
Low-capacity vet services	Service delivery	N/A	N/A	N/A	Negative
Frequency of field visits by veterinarians	Service delivery	Delivery	Field Visits	N/A	Positive
Poor accessibility to the veterinary clinic	Service delivery	N/A	N/A	N/A	Negative
(Distance travelled) Distant locations of the vet clinic	Service delivery	Delivery	Clinic Location	N/A	Negative
Wide range of provided services by veterinary clinics	Service delivery	Delivery		N/A	Positive
Low workforce/human resources in vet services	Service delivery	Delivery	Workforce	N/A	Negative
High services capacity	Service delivery	Delivery	Capacity	N/A	Positive
Weak service implementation	Service delivery	Delivery	Implementation	N/A	Negative
Frequency of field vaccination by a vet nurse	Service delivery	Delivery	Capacity	N/A	Positive

Table A2. *Cont.*

Variable (Factors)	Theme 1	Theme 2	Theme 3	Theme 4	Effect
Frequency of vet clinic visit	Service delivery	Delivery	Human	N/A	Positive
Lack of diagnostic equipment	Service delivery	Delivery	Human	N/A	Negative
Low MoA expenses	Service delivery	Delivery	Budget	Expenses	Negative
High dependence on farmers to vaccinate their livestock	Service delivery	Delivery	Implementation	N/A	Negative
Staff burnout	Service delivery	Delivery	N/A	N/A	Negative
Low incentives are given to vet workers	Service delivery	Delivery	Implementation	N/A	Negative
High feed support quantities	Service delivery	Delivery	Feed Support	Implementation	Positive
Trust in veterinary services	Service delivery	Delivery	N/A	N/A	Positive
Overburden on health services	Service delivery	N/A	N/A	N/A	Negative
Low MoA budget	Service delivery	Delivery	Budget	N/A	Negative
High expenses of feed support	Service delivery	Delivery	Feed Support	Expenses	Negative
Seek vet help	Service delivery	Delivery		N/A	Positive
Insufficient training; skills of the workforce	Service delivery	Delivery	Training	N/A	Positive
Loss of staff motivation due to unavailability of incentives	Service delivery	Delivery		N/A	Negative
Work force turnover	Service delivery	Delivery	Human Resources	N/A	Negative
Results return speed	Service delivery	Delivery	Laboratory	N/A	Positive
Availability of vaccination services at vet clinics	Service delivery	Delivery	N/A	N/A	Positive
Long waiting times for lab results	Service delivery	N/A	N/A	N/A	Negative
Veterinary laboratory high capacity	Service delivery	Delivery	Laboratory	N/A	Positive
Low levels of serious action conducted by the go	Service delivery	Delivery	Implementation	N/A	Negative
Increased of registered farmers	Service delivery	Delivery	Burden	N/A	Negative

Table A2. *Cont.*

Variable (Factors)	Theme 1	Theme 2	Theme 3	Theme 4	Effect
High reporting of livestock brucellosis cases (REPORTED)	Surveillance	Livestock	Reporting	N/A	Positive
Unknown outbreak statistics	Surveillance	Livestock	Reporting	N/A	Negative
Low traceability of brucellosis cases	Surveillance	Livestock	Reporting	N/A	Negative
Increased complaints	Surveillance	Human	Reporting	N/A	Positive
High reporting of human cases	Surveillance	Human	Reporting	N/A	Positive
Regular surveillance	Surveillance	Livestock		N/A	Positive
Individual livestock registry update	Surveillance	Livestock	Registration	N/A	Positive
Underreporting of brucellosis cases	Surveillance	Human	Reporting	N/A	Negative
Misdiagnosis of brucellosis cases	Surveillance	Human	Diagnosis	N/A	Negative
Patients not referred to a doctor	Surveillance	Human	referral	N/A	Negative
Correct vet case diagnosis of brucellosis	Surveillance	Livestock	Diagnosis	N/A	Positive
Traditional milk selling methods	Regulated Trade	Dairy	N/A	N/A	Negative
Household dairy production	Regulated Trade	Dairy	N/A	N/A	Negative
Traditional products sell rate	Regulated Trade	Prices	N/A	N/A	Negative
Livestock exportation	Regulated Trade	Livestock	Export	N/A	Positive
Ease of individual trade	Regulated Trade	Livestock	N/A	N/A	Negative
Unregulated individual trade	Regulated Trade	Livestock	Regulation	N/A	Negative
Unregulated livestock demand	Regulated Trade	Livestock	Demand	N/A	Negative
Costs of raising livestock	Regulated Trade	Livestock	Cost	N/A	Negative
High feed prices	Regulated Trade	Livestock	Price	Feed	Negative
Illegal livestock price	Regulated Trade	Livestock	Price	N/A	Negative
Financial losses for farmers	Regulated Trade	Livestock	N/A	N/A	Negative
Illegal cheap livestock importation	Regulated Trade	Livestock	Price	N/A	Negative
Feed (bran) black market price	Regulated Trade	Black Market	Feed	Feed Support	Negative

Table A2. *Cont.*

Variable (Factors)	Theme 1	Theme 2	Theme 3	Theme 4	Effect
Illegal livestock black market prices	Regulated Trade	Black Market	Feed	Price	Negative
Farmer's fear of financial loss	Regulated Trade	Livestock	Cost	Feed	Negative
Shared similar appearance between illegal and local livestock	Transmission Risk Factors	Livestock	Syrian Crisis	Syrian livestock	Negative
Open grazing area for livestock	Transmission Risk Factors	Location	N/A	N/A	Negative
Ease of movement of livestock	Transmission Risk Factors	Movement	N/A	N/A	Negative
Unregulated local livestock movement	Transmission Risk Factors	Movement	Regulation		Negative
Transboundary livestock black markets	Transmission Risk Factors	Movement	N/A	N/A	Negative
Shared water drinking tank for livestock	Transmission Risk Factors	Livestock	N/A	N/A	Negative
Traditional calendar (celebrations; etc.)	Transmission Risk Factors	Time	N/A	N/A	Negative
Improper consumption of livestock products	Transmission Risk Factors	Human	Consumption	N/A	Negative
Raw meat consumption	Transmission Risk Factors	Human	Consumption	Meat	Negative
Low levels of food safety	Transmission Risk Factors	Human	Consumption	Food Safety	Negative
Improper food processing tech (pasteurisation cheese)	Transmission Risk Factors	Human	Food Safety	N/A	Negative
Location of Syrian livestock owners	Transmission Risk Factors	Location	Syrian Crisis	N/A	Negative
Presence of *Brucella* in other animals (camel)	Transmission Risk Factors	Livestock	Mixing	N/A	Negative
Shared living environment (changed to desert)	Transmission Risk Factors	Livestock	Mixing	N/A	Negative
Mating with livestock of unknown origin	Transmission Risk Factors	Livestock	Mixing	N/A	Negative

Table A2. *Cont.*

Variable (Factors)	Theme 1	Theme 2	Theme 3	Theme 4	Effect
Lending rams between smallholders	Transmission Risk Factors	Livestock	Mixing	N/A	Negative
Increased livestock numbers in a farm	Transmission Risk Factors	Livestock	Mixing	N/A	Negative
Length of shared borders (high opportunity for livestock farming)	Transmission Risk Factors	Human	Location	N/A	Negative
Cultural traditions in consumption of dairy products	Transmission Risk Factors	Human	Cultural	N/A	Negative
Individual livestock slaughter	Transmission Risk Factors	Human	Hygienic Practices	N/A	Negative
Unsafe contact with livestock	Transmission Risk Factors	Human	Contact	N/A	Negative
Good human hygienic practices	Transmission Risk Factors	Human	Hygienic Practices	N/A	Positive
High livestock abortion rate	Transmission Risk Factors	Livestock	Hygienic Practices	Abortion	Negative
Safe livestock mixing	Transmission Risk Factors	Livestock	Mixing	N/A	Positive
Livestock local markets	Transmission Risk Factors	Livestock	Mixing	Trade	Negative
Shared traditional culture between smallholders	Transmission Risk Factors	Human	Trade	N/A	Negative
Syrian crisis	Transmission Risk Factors	Human	Syrian Crisis	N/A	Negative
Loss of grazing fields	Transmission Risk Factors	Livestock	Movement	Grazing fields	Negative
Ignorance of farmers to brucellosis risks	Transmission Risk Factors	Human	N/A	N/A	Negative
Lambing season	Transmission Risk Factors	Livestock	Time	N/A	Negative
Livestock movement to neighbouring countries	Transmission Risk Factors	Livestock	Movement	N/A	Negative

Table A2. *Cont.*

Variable (Factors)	Theme 1	Theme 2	Theme 3	Theme 4	Effect
Unregulated livestock migration	Transmission Risk Factors	Livestock	Movement	N/A	Negative
Disease-free imported livestock	Transmission Risk Factors	Livestock	Mixing	Regulation	Positive
Young age	Transmission Risk Factors	Human	Contact Awareness	N/A	Negative
Traditional and religious beliefs	Transmission Risk Factors	Human	Contact	consumption	Negative
Trust in imported livestock	Transmission Risk Factors	Livestock	Mixing	Importation	Negative
Low prices of dairy products	Transmission Risk Factors	Human	Consumption	Dairy Production	Negative
High Syrian diary production rate	Transmission Risk Factors	Human	Consumption	Dairy Production	Negative
Unregulated dairy production	Transmission Risk Factors	Human	Consumption	Dairy Production	Negative
Individual livestock ownership	Transmission Risk Factors	Human	safe livestock Products	N/A	Negative

N/A: Not available.

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