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Persistence of brucellosis in pastoral systems

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Summary

Regarded as a highly contagious, zoonotic disease with worldwide distribution, brucellosis is endemic in many countries and settings and is responsible for a considerable economic and health-related burden. Limited information is available on the persistence and prevalence of brucellosis in pastoral communities, due to the difficulty in gathering information and to their mobility. However, since these communities are economically and culturally dependent on livestock, it is important to further determine the cause of persistent disease and develop possible methods for its management. The two main objectives of this paper are to review the literature, identifying various epidemiological and social factors that affect the persistence of brucellosis in pastoral ecosystems, and determine prevalence estimates within these communities. The general trend of the summarised studies indicates low-level, relatively stable transmission of brucellosis in pastoral areas, when compared to transmission in intensive and semi-intensive peri-urban production systems. A formal mathematical analysis can be undertaken using matrix models or coupled differential equations. This allows an examination of the various conditions under which the number of diseased, infected or exposed animals remains stable. The authors examined an existing mathematical differential equation model for brucellosis in Mongolia for its equilibrium conditions and found it reasonably robust, though clearly more data are needed to estimate threshold densities for brucellosis transmission in other regions of the world. However, the results indicate the importance of livestock demographic determinants for brucellosis persistence. The paper concludes that brucellosis remains largely persistent in pastoral areas of the world, despite (varying) control efforts. Plans to control brucellosis in pastoral settings should include ecological considerations, such as sustaining ecosystem services in pastoral areas. This approach would include placing limitations on livestock stocking density, land reform, improved governance and integrated social and economic development.

Keywords

Brucella – Brucellosis – Disease persistence – Mathematical modelling – Pastoral ecosystem.

Introduction

Regarded as a highly contagious, zoonotic disease with worldwide distribution, brucellosis is endemic in many countries and settings, and is responsible for a considerable economic and health burden (22). A Gram-negative bacterium, *Brucella* mainly affects cattle, sheep, goats, camels and pigs, as well as causing human disease. The World Health Organization (WHO) estimates that a quarter of human cases go unreported, yet half a million cases per year are recorded (28). Humans are almost exclusively exposed to brucellosis through contact with animals and food of animal origin. Transmitted via human contact with secretions, predominantly through calving and abortions, this disease can also be spread through the consumption of contaminated, unpasteurised dairy products. Characterised by febrile illness in humans, the disease is often difficult to diagnose solely from the clinical picture, due to its similarities to other febrile diseases, such as malaria or typhoid fever (26). The main sign in animals is a high incidence of abortion (although this depends on the timing of infection – whether it is a recent infection or chronically present), as well as reduced fertility and milk yield. However, the disease can be present for several years without any clinical signs (2).

Because a primary sign of the disease is abortion in cattle and small ruminants, brucellosis can be an important disease in livestock, including large dairy herds, with severe economic consequences. The main risk of transmission to humans in these larger industrial settings is occupational. Yet smaller-scale farming systems, such as pastoral production, are also affected, due to the proximity between the animals and their owners, their mobile lifestyle and the traditional marketing of unpasteurised products. Pastoral systems often have limited access to public and veterinary health facilities, so it is difficult to control and eradicate the disease on a long-term basis (24, 25).

Pastoralism is described as the use of grassland grazing for the purpose of livestock production, with an estimated 100 to 200 million people living in this type of setting (www.cbd.int). Pastoralism is found predominantly in Africa, although it is also present in parts of Asia, South America and Europe. Roughly 16% of sub-Saharan Africa relies on a pastoral ecosystem, which is characterised by high mobility and low population density (6). This mobility supports a population based on seasonal water and pasture availability, in regions where landscapes are less productive. Pastoral systems can be categorised by mobility level, with classifications of 'highly nomadic', 'transhumant' and 'agro-pastoral' representing a full range of systems. Otte and Chilonda (21) have classified pastoral systems as grassland-based, with no crops, and a distribution of 1.5 humans per km^2, 1.9 cattle per km^2 and 1.27 cattle to every human.

Owing to the difficulty of gathering accurate information, data on the persistence and disease prevalence of brucellosis in pastoral communities are scarce. When considering possible disease-management strategies, it is vital to take into account the strong cultural and economic dependence on livestock amongst pastoral peoples. The two main objectives of this paper are to review the literature to identify the various epidemiological and social factors affecting the persistence of brucellosis in pastoral ecosystems, and to decide how to determine disease prevalence estimates within these specific communities.

The epidemiology of brucellosis in various pastoral regions

A thorough literature review was conducted using major databases, e.g. Blackwell Synergy, SpringerLink & Wiley Interscience, Web of Science, and Pubmed (www.ncbi.nlm.nih.gov/pubmed). The authors used the following search terms:

– *Brucella*
– *Brucella melitensis*
– *Brucella abortus*
– *Brucella suis*
– *Brucella canis*
– brucellosis
– pastoralism
– nomadic pastoralism
– infectious disease in nomadic settings
– pastoral ecosystems
– brucellosis in Europe, Asia, Africa, North America and South America
– brucellosis in camels, cattle, sheep, goats and humans.

Additional searches were conducted on non-governmental websites, such as the Food and Agriculture Organization of the United Nations (FAO), WHO and the World Organisation for Animal Health (OIE). The authors identified publications in which epidemiological data on the presence of brucellosis in nomadic settings were reported.

This review highlighted several factors that contribute to persistent disease circulation within the pastoral ecosystem. These ranged from biological, environmental, system-based and technical factors to host species, as discussed below. The regional differences in culture and environment among pastoral ecosystems determine the predominant livestock species which, in turn, determines the species of (host-specific) *Brucella* bacteria and the resulting effects on humans. According to the FAO website, pastoral systems can be classified by region, in that North and sub-Saharan Africa have a predominance of cattle and camels as livestock, while the Middle East and Europe tend to raise more small ruminants (11).

Europe, the Middle East and North Africa

In Greece, despite national brucellosis control programmes, the human incidence of the disease was recorded as 4.2 cases per 100,000 in 1998 (15), with rates rising to between 17.3 and 1,110 per 100,000 in certain rural areas where pastoralism is an important part of livestock-keeping (4). Since pastoralists use an estimated 23% of land in the Middle East and North Africa, the persistence of brucellosis is important in this area of the world, especially due to the presence of *B. melitensis* (in particular, biovar 3) in sheep and its transmission to humans (12). Human brucellosis in Saudi Arabia is mostly caused by contact with sheep and goats (8) in traditional Bedouin pastoral settings and linked to the consumption of raw milk, as well as direct contact with animal secretions during parturition. Human brucellosis is also present in Jordan, Iraq, Iran, Egypt, Oman and Libya, where there are extensive nomadic pastoral communities. In Jordan, the highest prevalence of brucellosis is found in cattle and sheep, whereas camels are the most important source of the disease in Iran, Egypt and Saudi Arabia, and goats are the primary contributor to human brucellosis in Iraq (14). These regions retain national disease surveillance and Health Service programmes, as well as large-scale therapeutic drug and vaccine campaigns. As these programmes generally control national disease levels in animals and humans, the main method of zoonotic brucellosis transmission is through the consumption of unpasteurised dairy products.

Asia

As in the case of the countries mentioned above, human brucellosis is a notifiable disease in China. In Mongolia, brucellosis is a significant problem amongst nomadic herding people, with human incidence rates of 115 per 100,000 in 1992 (10, 29). Despite vaccination campaigns, which began in 2000, brucellosis has re-emerged as a major preventable disease in Mongolia, partly due to low vaccine coverage and a sharp increase in livestock populations (22, 32). Data from the National Notifiable Disease Surveillance System for Inner Mongolia record a brucellosis prevalence of 29.2% among pastoral shepherds (30). In this area, the rise of human brucellosis over the past decade has been attributed to increases in the number of inexperienced workers in the agricultural sector in recent times. Similarly, Bonfoh *et al.* (7) found a representative human seroprevalence of 8%, which was statistically related to the seroprevalence of sheep brucellosis but not to that of goat or cattle brucellosis.

Latin America

In Latin America, Peru, Mexico and Argentina are the main countries affected by brucellosis (3). Some 565 human cases were reported in Argentina in 1996, and the main regions affected were those with large rural goat populations. Human brucellosis due to *B. melitensis* also occurs in Bolivia, Brazil, Colombia, Costa Rica and the Dominican Republic (5). Latin America is a very diverse area, with large differences in agriculture, climate, industry and livestock among its many countries. Despite routine vaccination measures in large-scale cattle operations, the disease is still present at low endemic levels throughout this region, a situation mainly attributed to remote small-ruminant herders (23).

Sub-Saharan Africa

In global terms, the majority of human and animal brucellosis is found in sub-Saharan Africa. With large pastoral communities, and the demand for meat and livestock products expected to double by 2050, brucellosis poses a major threat to this region and serious control efforts must be developed. The prevalence of the infection has been recorded at herd level, within-herd level and individual animal level. Some measurements of human brucellosis have also been made.

In summary, persistent disease was observed in most countries in the Sahel, with Ethiopia, Chad, Tanzania, Nigeria, Uganda, Kenya, Zimbabwe and Somalia reporting brucellosis in humans attributed to domestic cattle, camels, goats and sheep (18). Mangen *et al.* calculated an estimated seroprevalence of 16.2% (a range of 10.2% to 25.7%, with a 95% confidence interval) within cattle in sub-Saharan Africa, although this figure incorporates pastoral as well as other, more intensive, cattle-production systems (18).

Urban versus rural settings

Estimating the general incidence of brucellosis for a country or region is complicated by variations within these areas based on culture and herd breed, composition and size, as well as micro-climatic features. The literature reported marked differences in the brucellosis incidence between urban and rural settings, and between pastoral and nomadic settings. In Ethiopia, Megersa *et al.* (19) observed a higher seroprevalence of brucellosis in pastoral settings as compared to mixed farming. Similarly, in Argentina, there were differences in the prevalence of goat brucellosis between herds kept on farms (0.5% prevalence), as compared to nomadic mountain herds (0.8%) (23). In Argentina, 18 of the 212 human brucellosis cases reported between 1993 and 1995 originated from urban areas, while 118 came from rural areas and were associated with the consumption of unpasteurised goat's cheese (23).

Differences in disease prevalence also occur among the various animal species and the types of herd composition found in pastoral and urban systems. Urban systems tend to concentrate on one type of livestock species in a more intensive manner.

Herd size and composition

In pastoral systems, two main aspects of animal husbandry affect the prevalence of animal brucellosis. Larger herds, and those that include mixed species, appear to be more prone to disease circulation. As described in Mergesa *et al.* (19), several studies highlighted the higher disease prevalence recorded in cattle, in comparison to camels or smaller ruminants. As seen with cattle and sheep, the seroprevalence of brucellosis in camels reached 8% to 15% in animals kept in intensive urban settings, but only 2% to 5% in camels in pastoral systems (1). In a study in Somaliland, a prevalence of 3.1% was found in camels from nomadic and pastoralist herds, with the causative agent being almost exclusively *B. abortus* or *B. melitensis* (1). However, as described in Abbas *et al*., infection rates in camels kept in mixed-species herds usually depend on the disease level in the primary host species, which is usually cattle or sheep. A similar disease prevalence was found in pastoral camel herds in Ethiopia (5.5%) and Chad (3.8%), as described by McGrane and Higgins (17). Ghanem *et al*. (13) also described the effect of rearing camels together with small ruminants and cattle, with an increased level of brucellosis both at the individual animal and herd levels. Another factor affecting brucellosis in camels was herd size, with herds larger than 30 animals being more affected by the disease (13).

Livestock densities

The general trend indicates low levels and relatively stable transmission of brucellosis in livestock (cattle, sheep and goats) in pastoral areas, when compared to intensive and semi-intensive peri-urban production systems. These observations match with the epidemic theory of endemic stability. Endemic stable transmission of an infectious disease means that the incidence of the disease does not change and the effective reproductive ratio (i.e. the number of secondary infections from one infectious individual) is very close to one. A formal mathematical analysis can be undertaken using matrix models or coupled differential equations. Using differential equations allows an examination of the various conditions under which the number of diseased, infected or exposed animals remains stable. The authors examined an existing mathematical model for brucellosis in Mongolia for its equilibrium conditions (32).

This analysis concentrates on the transmission between livestock in a non-age-, non-sex-structured model (Fig. 1). Briefly, susceptible sheep and goats (U), which graze together, become seropositive (V). The authors assume lifelong seropositivity of sheep and goats. Similarly, susceptible cattle (X) become seropositive (Y) and remain so for their lifetime. For the change in the number of susceptible sheep, we can write equation 1, where α is the annual birth rate, which is influenced by a brucellosis-seroprevalence-dependent (V/U+V) reduction, η, of the annual birth rate. The mortality rate, μ, represents the susceptible (U) and the seropositive animals (V), γ is the proportion of infectious animals among the seropositive animals and β is the transmission constant. To explore conditions for a stable number of seropositive animals, equation 2 is set to zero. The transmission of brucellosis is ongoing, as long as the effective reproductive ratio is greater than one (equation 3). The effective reproductive ratio (R_e) indicates the number of secondary infections for each infectious individual during ongoing transmission. It can be derived by dividing all positive terms by all negative terms on the right-hand side in equation 2.

$$\frac{dU}{dt} = \alpha\,(U+V)\,\left(1-\eta\,\frac{V}{(U+V)}\right) - \mu U - \gamma\beta UV \qquad (1)$$

$$\frac{dV}{dt} = \gamma\beta UV - \mu V \qquad (2)$$

$$R_e = \frac{\gamma\beta U}{\mu} \qquad (3)$$

If R_e is greater than 1, the number of infected animals increases. When R_e is equal to 1, the number of infected animals remains constant, and if R_e is less than 1, the number of infected animals decreases and could stabilise in a new equilibrium. The proportion of infectious animals among the seropositives is determined by the patho-physiology of brucellosis and is not likely to change. The transmission constant, β, is made up of the multiplicative relationship of the probability of transmission (the virulence of the bacterium and the contact patterns between animals) during social and environmental contact patterns between animals. In extensive pastoral systems, which remain similar over relatively long time periods, β is not likely to change significantly. Similarly, the mortality rate, μ, can be assumed to be relatively constant, while offtake (slaughtering rates) may vary (32). A decrease in offtake, as has been observed in Mongolia since the end of the Socialist period in 1990, may increase R_e (32). The remaining number of susceptible small ruminants (U) depends on the reproduction, mortality and offtake and is probably the most variable quantity. The authors examined the threshold value of the number of susceptible small ruminants (U) to maintain an R_e above one. They modified the parameter values by considering the geo-spatial density of the animals and solved equation 1 for R_e (equation 3). To obtain animal densities, absolute totals of animal numbers were divided by 1,210,000 km^2 of arid grasslands suitable for pastoral grazing in Mongolia (27). Minimum and maximum values were taken from the sensitivity analysis in Zinsstag *et al.* (see Table I, p. 80, in 32).

In Figure 2, the density of small ruminants and cattle per square kilometre was plotted against R_e. We can observe that R_e drops below 1 at approximately 1.2 (min. 0.6; max. 8) cows/km^2 and at about 6.8 (min. 4.5; max. 21) small ruminants/km^2. As densities increase, R_e increases too, but in pastoral areas, without any other external feed input, livestock numbers remain within certain limits (www.fao.org/AG/againfo/resources/documents/).

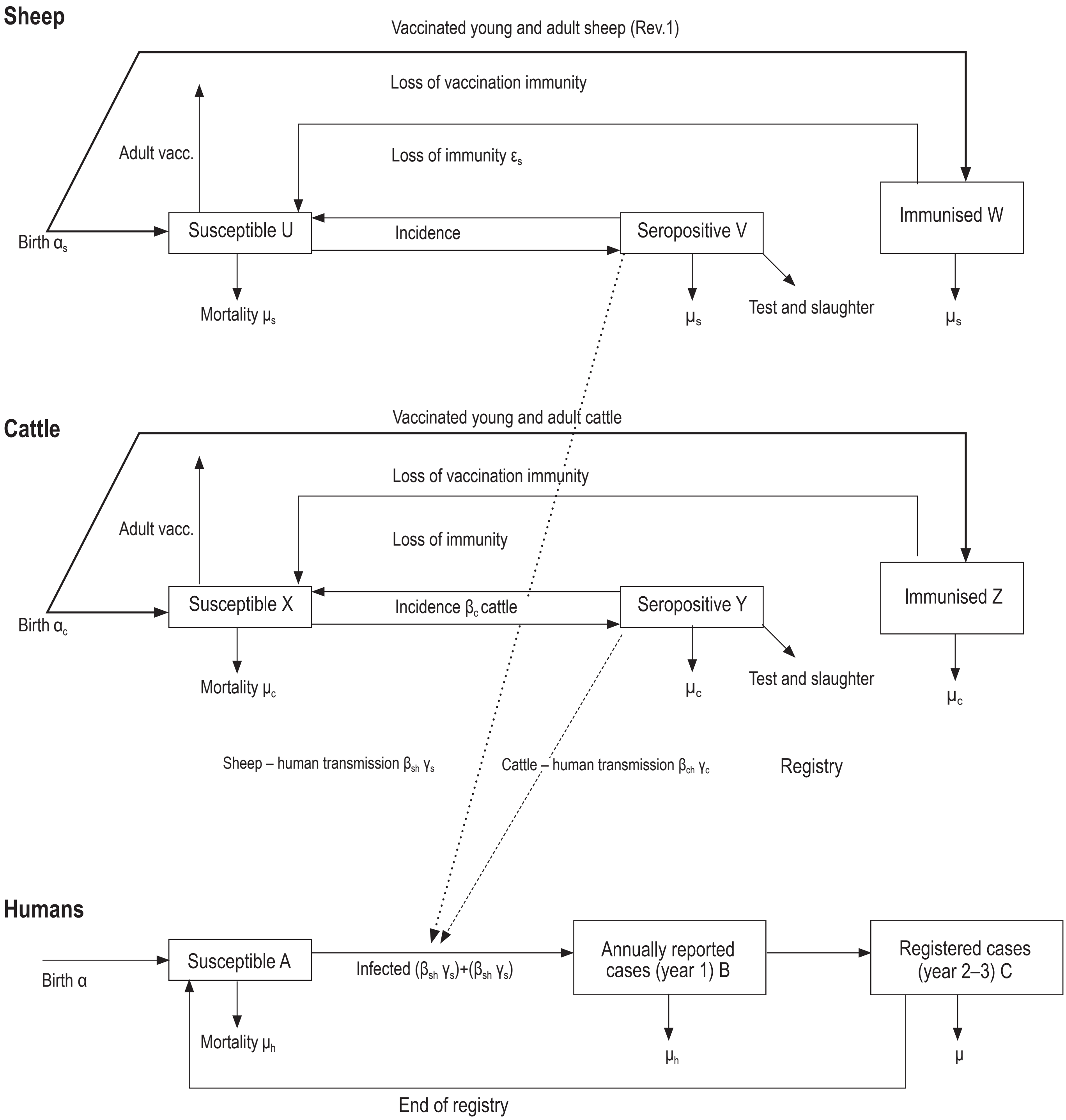

Fig 1
Model for joint human – animal brucellosis transmission in Mongolia

Discussion

This study reviews the current status of brucellosis in livestock in pastoral areas of the world and uses a simple mathematical model to analyse theoretical conditions for its persistence. The authors' conclusions about the dependence of brucellosis transmission on threshold animal densities should be considered with caution, because of a series of assumptions. In most situations, animals are not homogeneously distributed, which leads to higher densities in key areas, e.g. at watering holes or markets. The analysis

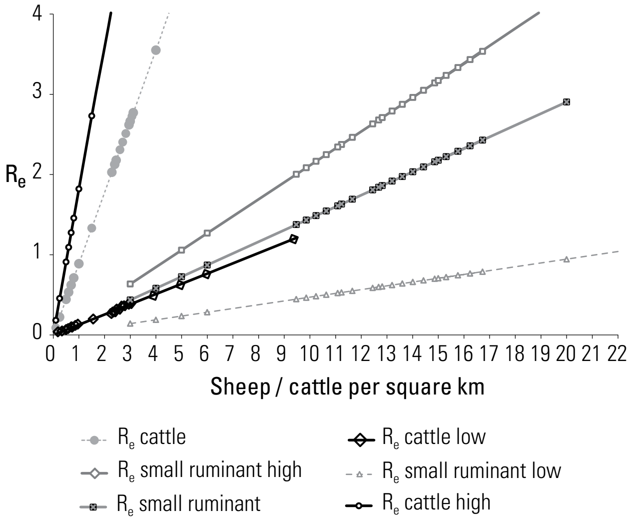

Fig. 2
Relationship of the effective reproductive ratio, R_e, of brucellosis and the geospatial density of cattle and small ruminants in Mongolia

is based on published data from Mongolia, which has particular geoclimatic conditions, and thus these findings should not be extrapolated directly to other areas. It is clear that, in order to estimate threshold densities for brucellosis transmission in other regions of the world, more data are needed.

Given these constraints, the authors' analyses indicate the importance of demographic determinants for brucellosis transmission in pastoral systems. The authors used a simplified mathematical model without age or sex structure. A model structured to include age and sex may well lead to oscillatory behaviour of R_e. Improved age- and sex-structured mathematical models of brucellosis transmission are needed for more realistic assessments of the persistence of transmission. Brucellosis control should not be disconnected from close monitoring of livestock populations, which also has implications for sustainable pasture management.

Brucellosis is already a complex disease, yet factors such as climate can further complicate control and elimination efforts. Drought and dry seasons can result in severe animal stress, making them more susceptible to a variety of diseases. Wet seasons usually coincide with parturition (19), which presents an accelerated means of disease transmission, not only through the aborted or live animals, but also through ease of access to contaminated water and feed sources (20). In Central and East Asia, seasonal climate variation is equally important, with parturition taking place mostly during spring, when temperatures are still extremely cold, as seen in Mongolia, Kazakhstan or Kyrgyzstan. At such low temperatures, *Brucella* may persist for longer periods in the environment, leading to the risk of direct transmission (9). As a result of the nature of pastoralism, which is principally dictated by climate and resource availability, seasonal climate variation may play an important role in the persistence of brucellosis in these communities.

Another challenge in combating brucellosis in pastoral systems is the difficulty of correct diagnosis. In pastoral systems, human brucellosis is often confused with other febrile illnesses, especially malaria and typhoid fever (26). As mentioned, brucellosis can also be present subclinically, making control and surveillance efforts more difficult. Animals can also have sub-acute and chronic disease, hence its persistence at low endemic levels throughout the year (28). As with other public-sector Animal Health Services, the surveillance and control of brucellosis in sub-Saharan Africa is rarely implemented outside southern Africa, which may signal a lack of awareness of its presence, resulting from poor diagnostic capacity (16).

Throughout the literature review, the levels of disease reported appeared to be dependent on the diagnostic test used. Initial testing with the Rose Bengal test (RBT) is usually conducted as a sensitive rapid screening test yet, due to *Brucella*'s cross-reactivity with other bacteria, further serial testing – through the complement fixation test (CFT), serum agglutination test (SAT), competitive enzyme-linked immunosorbent assay (c-ELISA), and, most recently, the fluorescence polarisation assay (FPA) – is needed to confirm the disease and species. Serial testing increases specificity, but also increases the chances of misdiagnosing true-positive cases (19). Since pastoralism involves a lack of stable diagnostic facilities and access to veterinary and public health professionals, the disease is likely to remain untreated in many nomadic settings, with both humans and livestock being infected.

As described in a WHO report (28), brucellosis should be diagnosed at the herd level, due to the incubation period in infected animals, the presence of serologically negative animals, and the expected presence of false-negative results. Animal vaccines, such as *B. melitensis* Rev.1 and *B. abortus* S19, play an important role by reducing transmission. Several countries, including Mongolia and Kyrgyzstan, have recently adopted conjunctival vaccination, which is recommended by the OIE.

The authors conclude that brucellosis persists in pastoral areas of the world, despite varying efforts at control. While diagnostic tests for brucellosis and methods for its control and elimination are well understood (33), this disease remains largely unrecognised, under-diagnosed and uncontrolled in a large number of the pastoral areas of the world, particularly in Africa. Causes for its persistence involve multiple social and ecological factors, including lack of access to services, poor governance, large distances, harsh climatic conditions, herd composition and animal geospatial density. Using a systemic analysis to untangle the lack of effectiveness of control efforts in a given social-ecological system would allow us to identify the most important factors hindering intervention strategies (31, 34). Plans for brucellosis control in pastoral systems should also include ecological considerations, such as maintaining the ecosystem services of pastoral areas. Such an approach would involve limiting livestock densities, land reform, improved governance, and integrated social and economic development.

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La persistance de la brucellose dans les aires pastorales

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Résumé

La brucellose est une zoonose très contagieuse distribuée mondialement, qui sévit à l'état endémique dans de nombreux pays et contextes avec un impact sanitaire et économique très lourd. Rares sont les informations disponibles sur la persistance et la prévalence de la brucellose dans les communautés pastorales, en raison des difficultés d'y obtenir ces informations et de la mobilité des populations concernées. Néanmoins, celles-ci dépendent économiquement et culturellement de l'élevage, de sorte qu'il est important d'arriver à déterminer les causes de la persistance de l'infection brucellique et de mettre au point des méthodes réalistes de gestion. Le présent article a pour buts, d'une part de faire le point sur la littérature existante sur le sujet en mettant en relief les divers facteurs épidémiologiques et sociaux qui influent sur la persistance de la brucellose dans les écosystèmes pastoraux et, d'autre part, d'estimer la prévalence de la maladie au sein de ces communautés. Les tendances générales révélées par cette revue bibliographique indiquent que la transmission de la brucellose dans les zones pastorales se maintient à un niveau faible et relativement stable comparativement à celle observée dans les systèmes de production intensifs, semi-intensifs et périurbains. Une analyse mathématique formelle peut être entreprise, au moyen de modèles matriciels ou d'équations différentielles couplées. Cette méthode permet d'étudier les différents paramètres qui concourent à stabiliser le nombre d'animaux malades, infectés ou exposés. En particulier, un modèle d'équation mathématique différentiel appliqué à la brucellose en Mongolie et aux conditions influant sur son équilibre présente un degré acceptable de robustesse, mais il sera évidemment nécessaire d'y intégrer davantage de données afin d'évaluer les seuils de densité qui permettent la transmission brucellique dans d'autres régions du monde. Ces résultats montrent néanmoins que les caractéristiques démographiques des populations d'animaux d'élevage jouent un rôle déterminant dans la persistance de la brucellose. Pour conclure, les auteurs constatent une persistance importante de la brucellose dans les aires pastorales, en dépit des efforts qui y sont déployés à des degrés divers pour la contrôler. La lutte contre la brucellose dans les milieux pastoraux doit être planifiée en prenant en compte les aspects liés à l'écologie, par exemple la durabilité des services écosystémiques rendus par ces milieux. Une telle approche passe notamment par la limitation de la densité du bétail, par une réforme agraire, par une meilleure gouvernance et par un développement social et économique intégré.

Mots-clés

Brucella – Brucellose – Écosystème pastoral – Modélisation mathématique – Persistance d'une maladie.

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Persistencia de la brucelosis en sistemas pastorales

V. Racloz, E. Schelling, N. Chitnis, F. Roth & J. Zinsstag

Resumen

La brucelosis, considerada una enfermedad zoonótica sumamente contagiosa con distribución planetaria, es endémica en gran número de países e instalaciones y es causa de considerables pérdidas económicas o ligadas a problemas sanitarios. Hay escasos datos sobre su persistencia y prevalencia en las comunidades dedicadas al pastoreo, debido a la dificultad de reunir información y a la movilidad de esas gentes. Sin embargo, puesto que las comunidades de pastores dependen económica y culturalmente del ganado, resulta importante discernir con más precisión la causa de toda enfermedad persistente y dar con posibles métodos para combatirla. Los autores persiguen básicamente dos objetivos: analizar la bibliografía y determinar los distintos factores epidemiológicos y sociales que influyen en la persistencia de la brucelosis en los ecosistemas pastorales; y tratar de estimar la prevalencia en esas comunidades. Comparada con la transmisión de la brucelosis que se da en sistemas periurbanos de producción intensiva o semi-intensiva, en las zonas de pastoreo la tendencia general de los estudios resumidos parece apuntar a una transmisión de baja intensidad y relativamente estable. Es posible proceder a un análisis matemático empleando modelos de matrices o ecuaciones diferenciales acopladas, lo que permite estudiar las diversas condiciones en que el número de animales enfermos, infectados o expuestos se mantiene estable. Los autores examinaron un modelo ya existente de ecuación diferencial referida a la brucelosis en Mongolia y a sus condiciones de equilibrio, y lo juzgaron razonablemente robusto, aunque a todas luces se necesitan más datos para estimar las densidades que constituyen el umbral de transmisión de la brucelosis en otras regiones del mundo. No obstante, los resultados ponen de manifiesto la importancia que revisten los determinantes demográficos del ganado para la persistencia de la enfermedad. Los autores llegan a la conclusión de que, a pesar de las (heterogéneas) medidas de control instituidas, la brucelosis es mayoritariamente persistente en las zonas pastorales del mundo. Todo plan de lucha antibrucélica en zonas de pastoreo debería integrar consideraciones de índole ecológica, como el mantenimiento de los servicios ecosistémicos en esas zonas. Ello supondría asimismo definir límites de densidad de estabulación del ganado y tener en cuenta aspectos como la reforma agraria, la mejora de la gobernanza o el objetivo de un desarrollo social y económico integrado.

Palabras clave

Brucella – Brucelosis – Ecosistemas pastorales – Modelización matemática – Persistencia de enfermedad.

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