Veterinaria Italiana, **43** (2), 317-326

Simple models to assist in communicating key principles of animal disease control

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Summary

Aggressive actions for disease eradication, including animal disposal, can have serious impacts on the livestock industry, environment and public confidence. Coordinated efforts are required for effective, efficient and acceptable disease control and eradication. The authors summarise concepts from previous publications into a group of simple examples, schematic diagrams and basic equations. These simplified models may be used to communicate principles of disease control to livestock owners and workers, and to regulatory officials and policy-makers. Such stakeholders may not have time to study more complex models. It is hoped that a broader appreciation of key principles will compel stakeholders to act routinely in a manner that improves the prevention and control of infectious animal diseases.

Keywords

Animal diseases, Animal disposal, Communication, Control, Livestock, Models, Stakeholders.

Semplici modelli per l'aiuto nella comunicazione dei principi chiave del controllo delle malattie animali

Riassunto

Azioni aggressive per l'eradicazione delle malattie, compreso lo smaltimento degli animali, possono avere un impatto notevole sulle attività di allevamento, sull'ambiente e sulla sicurezza pubblica. E' richiesto uno sforzo coordinato per l'efficace, efficiente e accettabile controllo e eradicazione delle malattie. Gli autori riassumono i concetti delle precedenti pubblicazioni attraverso un gruppo di esempi, diagrammi schematici e equazioni di base. Questi modelli semplificati possono essere utilizzati per comunicare i principi per il controllo delle malattie ai proprietari e agli addetti ai lavori degli allevamenti, ai funzionari pubblici e ai legislatori. Tali utilizzatori non possono avere tempo a disposizione per studiare modelli più complessi. Si auspica che una maggiore comprensione dei principi chiave costringerà gli interessati ad adottare abitualmente comportamenti finalizzati a migliorare la prevenzione e il controllo delle malattie infettive degli animali.

Parole chiave

Bestiame, Comunicazione, Controllo, Malattie animali, Modelli, Smaltimento degli animali, Utilizzatori.

Introduction

Industry and trade run smoother when the flow of inputs and outputs is steady and predictable. Most people are willing to work hard to achieve a sufficient and predictable flow of income. Unpredictable disruption of flow can cause hardship with impacts over an extensive range of the system. Contagious or just infectious livestock and poultry diseases can disrupt the flow of the agri-food industry and trade (22, 23, 24, 28). This can sometimes cause significant negative impacts on the

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broader economy and even on public health (4, 7, 10). Coordinated actions are required across the entire system, from frontline animal husbandry workers to international agri-food policy-makers (6).

Stakeholder understanding of the key factors influencing disease spread is important. Stakeholder appreciation of how their personal actions contribute to disease spread may compel them to act in ways that prevent and control infectious animal disease. This can help to reduce a disruption of flow to their income.

Models may be used to help people understand principles of disease spread and factors that influence disease prevention and control. Several models have been developed, as described and reviewed previously (17, 20, 21, 30). Various approaches have been used. Examples include mathematical models (1, 8, 9, 12, 16) and spatially explicit, stochastic, state-transition computer-simulations (11, 14, 25, 26, 27, 29). The objective of this paper is to summarise key concepts from previous publications into a group of simple examples, schematic diagrams and basic equations. These simplified models may be used to communicate key principles of disease prevention and control to animal health stakeholders.

Examples and schematic diagrams of infectious disease spread

Readers may consider their personal experience with the spread of a common cold among people in their household, workplace and community. Suppose each infected person 'gives' their cold to two other people, and each of those people then 'give' their colds to two more people. Figure 1 is a schematic diagram of such exponential spread between units. Potential units include people (e.g. spreading a cold), or livestock farms (e.g. spreading foot and mouth disease [FMD] among farms). The number of new cases that are generated for each existing case (two in this example), is very important in determining if the outbreak expands, stabilises or decreases over time, in the population. This number is known as the reproductive rate (R) (1).

When R is greater than 1 (i.e. if on average, each infected unit infects more than one new unit), then the number of newly infected units continues to increase. In this example with a consistent R=2, the fifth 'generation' (after the original case) creates 32 (or 2^5) newly infected units. This brings the total number of infected units to 63. This schematic diagram also illustrates that since the number of newly infected units can increase exponentially, so too can control actions have preventive impacts that are exponential in nature. For example, if disease transmission is blocked at unit 'A' in Figure 1, then all subsequent branches from 'A' (30 cases), can be prevented. This schematically illustrates the important contribution individual producers can make to their industry, far beyond their own farm, by practising effective biosecurity and contact control, preventing spread of disease on and off their farms.

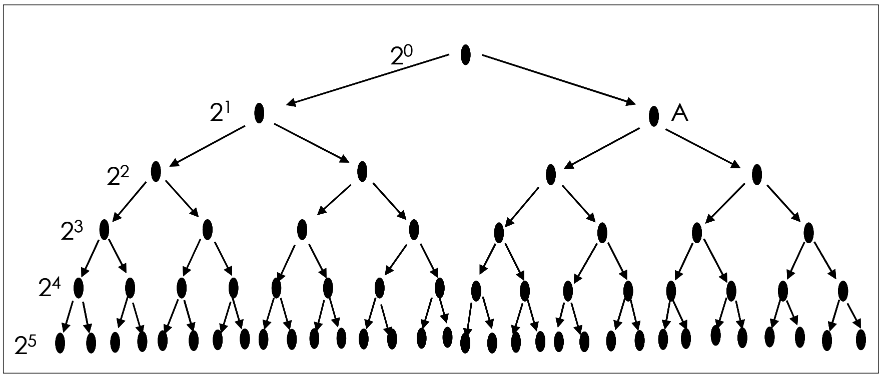

Figure 1
Schematic diagram of exponential increase in number of cases if each existing case infects two new cases (reproductive rate R=2)

Better biosecurity, faster detection, better tracing and influential hubs

Figure 2 schematically summarises four different scenarios of an outbreak of an infectious animal disease among farm units. The scenarios vary in their levels of biosecurity, contact management, disease detection and tracing effectiveness. Scenario 'a' represents poor biosecurity and contact management resulting in an R=2, plus slow detection and no tracing. This leads to initial official awareness of only one case, sometime after the start of the outbreak, but 62 infected units remain as yet unknown to the authorities. It can be very difficult for industry and regulatory authorities to regain control of disease spread in such situations.

Scenario 'b' represents poor routine biosecurity with an initial R=2, but better official detection (i.e. one generation earlier than scenario 'a', at the unit labelled 'i'), coupled with better tracing. Note the quarantine of 'i' preventing further spread from 'i', and the forward-tracing and subsequent quarantine of the unit previously infected by 'i'. Also note the backward tracing to source infection units and subsequent forward-tracing from backward traces, to identify infected units and enforce quarantine to prevent further spread. Furthermore, note that general movement controls are having some effect, preventing transmission from some as yet unknown infected farms relative to scenario 'a'. In scenario 'b', this all leads to relatively rapid official awareness of 12 cases, but 28 unknown cases remain in the background. There continues to be significant spread, but R has been decreased from its initial value of 2.

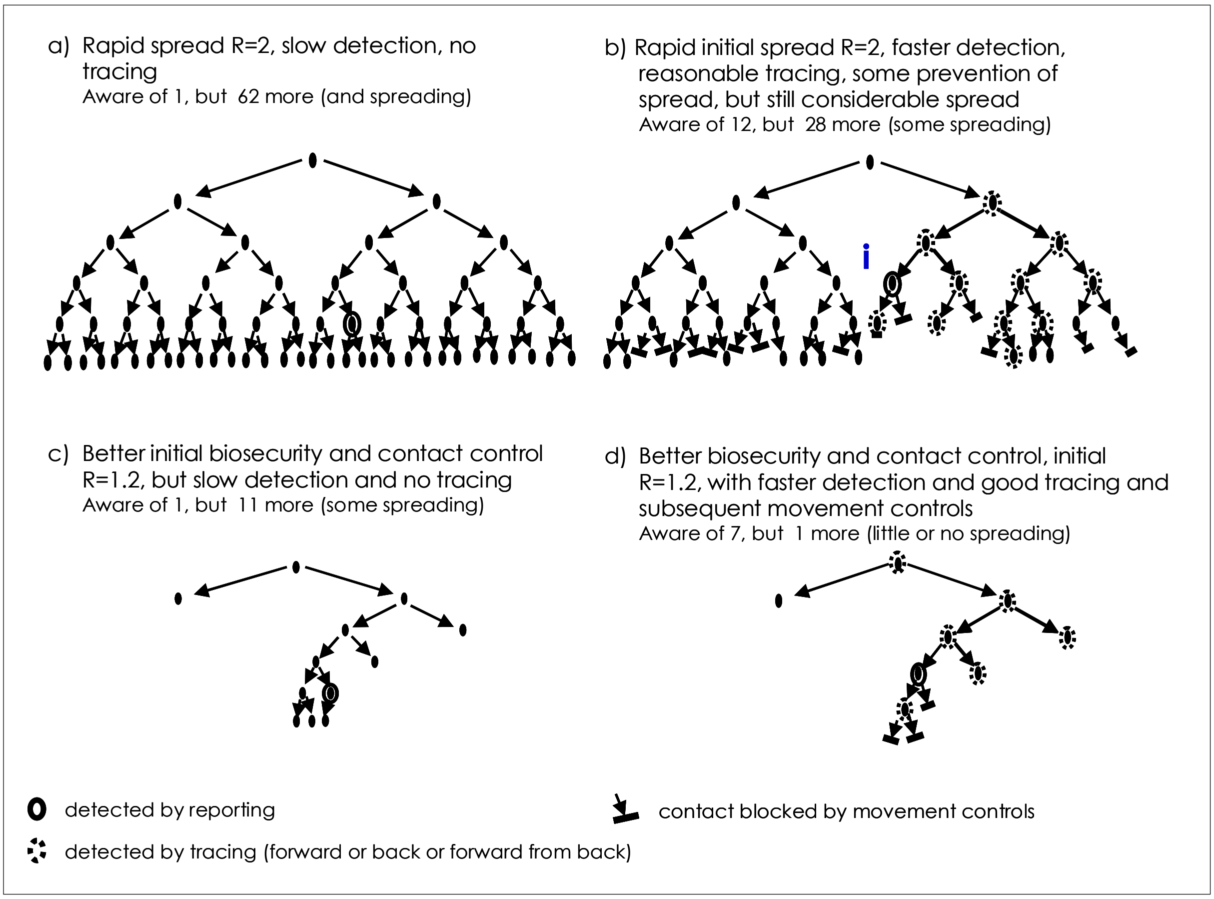

Figure 2
Schematic diagram of four scenarios

Scenario 'c' represents better routine biosecurity and contact management, such that the early R (i.e. before officials are aware of the outbreak) is down to an average of 1.2 new cases arising from each existing case. Even with slow detection and no tracing, like that of scenario 'a' , this leads to a situation of one case initially known to authorities, but 11 unknown cases still in the background.

Scenario 'd' represents good routine biosecurity and contact management leading to an initial R of 1.2, plus earlier detection, plus good tracing and reporting; leading to an official awareness of seven cases and one as yet unknown case in the background. It is interesting to note that biologically, scenario 'd' is a much better situation for industry and regulatory officials to be in than scenario 'a'. However, initially, scenario 'd' would probably be reported in the press in a manner that would sound much worse (seven known cases) than scenario 'a' (one known case), because the press would be unaware of the potential hidden cases in scenario 'a'. Over the subsequent days and weeks of scenario 'a', officials might detect most of the as yet unknown cases, only to realise how far behind they were in control of spread that had occurred from those infected units in the interim.

It is important that livestock workers, owners and traders understand that the likelihood of their industry facing scenarios similar to 'a', 'b', 'c' or 'd' is influenced greatly by their individual and group efforts, before and during an outbreak. Their routine 'peacetime' practices of movement control and biosecurity greatly influence the R of disease spread, before officials become aware of an outbreak. Their observation of livestock for signs of infection and the speed with which they seek veterinary and laboratory diagnoses influences how rapidly serious disease is detected and controls are implemented. Furthermore, the ease of analyses of movement and contact records, as updated by industry, influence the speed and accuracy of traces and the precision of targeted disease control efforts by officials. Veterinary, laboratory and emergency response infrastructure are also important.

The above examples assumed an equal number of contacts by infected individuals or farms. Recent studies of animal movements in Great Britain (5) and Denmark (3) have demonstrated that while most livestock operations have a few contacts, some may act as super-spreaders due to their interactions with a high number of other units (e.g. markets, dealers), in scale-free contact networks (2, 18). Figure 3 schematically illustrates the impact of a hub (h) or super-spreader. Note the above average number of new cases generated from 'h'. In this example, the average R is 1.6 (36/22), but unit 'h' is responsible for the creation of 17 new cases. If the new cases arising from 'h' are excluded, the average R is 0.9 (19/21), which is less than 1. From a disease control point of view, this illustrates the importance of avoiding the creation of such hubs, or ensuring extremely rapid control of infection and transmission from such hubs, during an outbreak.

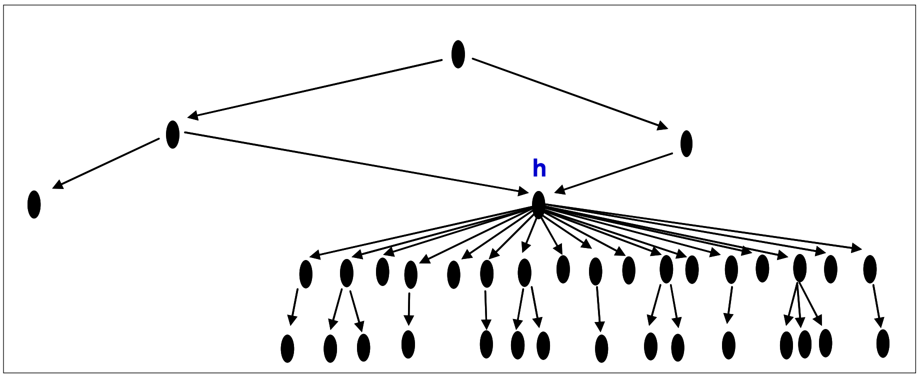

Figure 3
Schematic diagram of extensive disease spread from an active 'hub' (h) or super- spreader in scale-free contact networks

A simple equation of key factors that influence disease spread and control

The reader may consider key factors that influence the number of people to whom they transmit or 'give' their cold or infection. This can be thought of as their personal R, in terms of the number of new cases they create, from themselves as an infectious case. Self-evident influential factors include:

- the duration (D) or number of days that they are available as an infectious case (e.g. 5 days)
- the frequency of contacts they make (C) during that time (e.g. 5 contacts per day)
- the probability of transmission (T) per contact (e.g. 20%)
- the probability that persons they contact are susceptible (S) (e.g. 40% of contacts are with susceptible people). Thus, a simplified equation for R (1) may be viewed as:
  - R = D × C × T × S which in this example leads to:
  - R = 5 infectious days/case × 5 contacts/day × 0.2 transmissions/contact × 0.4 new cases/transmission
  - R = 2 cases/case, is thus a 'unit-less' number, with new cases in the numerator that were derived from old case(s) in the denominator, as per the defintion of R.

The proportion of people who are susceptible (S) can also be thought of as:

[1- (the proportion who are not susceptible)], where the proportion who are not susceptible include:

- the proportion who are already infected (I) and are naturally immune
- the proportion who are immune through vaccination (V) for the disease in question
- the proportion who are deliberately removed (or missing [M]) from exposure, with the intent of preventing exposure and stopping spread. Thus, the above formula may be rewritten (replacing susceptible S), as:

  $R = D \times C \times T \times [\, 1 - (\, I + V + M\,)\,]$.

This simple formula summarises key factors that influence the spread of infectious disease through a population and thus key factors or combinations of factors that must be altered to control or eradicate disease. It is important to note that R decreases as I increases, even if the other factors remain constant. This means that all things being equal, the number of new cases produced per existing case will decrease on its own, over time, as the proportion susceptible decreases because the proportion infected has increased. Therefore, as long as susceptible units are not added to the population by immigration, births or loss of immunity, then R will eventually drop below 1 and the outbreak will 'burn itself out' naturally. It is also important to note that the reproductive rate R will be decreased by decreasing any combination of the duration available as infectious (D), contact frequency (C), transmission probability (T), or proportion susceptible (S) (i.e. by increasing proportion infected [I], vaccinated[V], or missing [M]).

Some examples of actions that can be taken to decrease the duration (D), i.e. the number of days that existing cases remain infectious, include: staying at home to rest when you have a cold (thereby reducing the duration of time you are available to make contacts and perhaps reducing the duration you are actually infectious), effective disease surveillance and rapid diagnosis to reduce the duration of time during which there are no controls on infected farms (i.e. early detection, thereby reducing the duration before quarantine starts), depopulation of animals on known infected farms, or pre-emptive depopulation of infected but not yet infectious animals (D=0).

Examples of actions to decrease the contact frequency per day while available as infectious (C), include: avoiding meeting people at work as much as possible (if you cannot stay at home when you have a cold), routinely minimising movement on-and-off farms to only essential traffic, restricting the number of different contact farms and the frequency of contacts per farm, establishing direct trading that minimises or eliminates high contact hubs (potential super-spreaders) and stringent quarantine and movement controls during outbreaks. Decreasing C caused by airborne spread is more difficult.

Examples of actions to decrease the probability of transmission (T) per contact, include the following: frequent washing of hands, not shaking hands or kissing to greet people while you have a cold, isolating additions to a herd, all-in-all-out practices, and cleaning, disinfecting, or treating contaminated or potentially contaminated materials or equipment before allowing direct or indirect contact with susceptible animals.

Examples of actions that can be taken to decrease the proportion of the population susceptible (S) include: deliberately infecting animals (I) at a time in the production cycle when infection causes less impact (e.g. porcine reproductive and respiratory syndrome in young breeding stock), increasing the proportion immune by vaccination (V) and increasing the proportion that are missing (M) (i.e. deliberately removed), so as to be not available for infection even though they would otherwise be susceptible. This proportion 'missing' (M) may be increased by physically removing susceptible animals by relocation, or preferential slaughter for consumption, or pre-emptive depopulation of non-infected animals at risk. Increasing immunity by deliberate infection (I), vaccination (V) or removal (M) are analogous to establishing a 'fire-break' where fires are controlled by decreasing susceptible (S) fuel.

Precise scalpel vs blunt hammer

Biologically, it does not matter which combination of variables D, C, T, V or M are altered to achieve R<1, to bring an outbreak under control. However, the challenge to achieving R<1 efficiently is in lowering D, C or T with a precision that is limited to truly infected units, with minimal restrictions to normal activities among non-infected units. Excellent surveillance, rapid diagnostic testing systems with high sensitivity and specificity, effective quarantine and movement controls of truly infected units, and excellent biosecurity, effective cleaning, disinfection and treatments, are all important to efficiently and effectively lower D, C and T among truly infected units. Precision is also required to increase V or M efficiently, only among units truly at risk of becoming infected. For example, accurate knowledge of the contribution and characteristics of airborne spread in the specific outbreak will help to target the amount and location of V or M more precisely down-wind, if appropriate. Similarly, accurate specific knowledge of direct and indirect movements will help to target the application of M through more precise application of pre-emptive culling or removal only among units truly at higher risk of infection.

Depending on the situation, appropriately precise, timely, effective and efficient manipulation of D, C, T, V and M may not be technically or logistically feasible. Different combinations will be achievable or required under different situations. For example, if desired disease reporting, tracing, movement restrictions and biosecurity protocols (designed to reduce D, C and T), are not being implemented appropriately by livestock owners and workers; then officials may need to rely on broader, less precise, animal destruction (reducing D and increasing M) and vaccination (V), to gain control. Similarly, if airborne spread is a significant component of contact (C) and transmission (T), then even perfectly implemented movement and biosecurity restrictions may not reduce C and T sufficiently. In such cases, increasing vaccination (V) and removing a greater proportion of the susceptible population (i.e. increasing M), may be required to obtain R<1. Therefore, considerable understanding, data, risk assessment and judgment are required to make appropriate decisions for altering D, C, T, V and M effectively and efficiently, with the precision of a scalpel verses the bluntness of a hammer (13, 15, 19).

It may be simple but it's not easy

The concepts described above may be simple to understand. However, assigning them accurately and precisely during an outbreak is not easy. Figure 4 may be viewed as a more complex version of Figure 1. It schematically illustrates the temporal overlap of infected units of various generations of disease spread. It also illustrates how some cases and contacts may remain unknown to authorities for some time, or perhaps never be identified. Estimating the current or most recent R, in terms of the average number of new cases generated per infectious case, is not easy during an outbreak. This is because newly detected cases may actually be old cases, and several cases may not yet be detected. In addition, the exact dates of infection and infectious periods of units are rarely known as precisely as implied in Figure 4. Also, obtaining true measures of D, C, T, I, V and M during an outbreak is difficult. Furthermore, since different combinations of D, C, T, I, V and M can result in the same R, it is possible to fit untrue combinations of variables to generate the observed (accurate or inaccurate) R.

Figure 4 schematically illustrates a scenario of true spread among farm units of a generic infectious animal disease. The time units (e.g. days) increase down the left-hand side of the figure. The rectangles represent truly infected herds that are either known or as-yet unknown to authorities. The vertical placement and length of each rectangle represents the relative dates and duration of the combined latent and infectious periods of the respective herd unit. Hollow green rectangles represent herds known to disease control authorities as infected, found by reports to authorities or by successful traces (forward or backward) from known cases. The vertical location of the asterisk within green rectangles corresponds to the relative day (in the left-hand time scales) when the authorities became aware of the infected herd. The solid blue rectangles represent infected herds that are as yet unknown to authorities. The arrows represent direct, indirect or airborne contacts that truly caused the spread of infection between the specific units indicated, on the

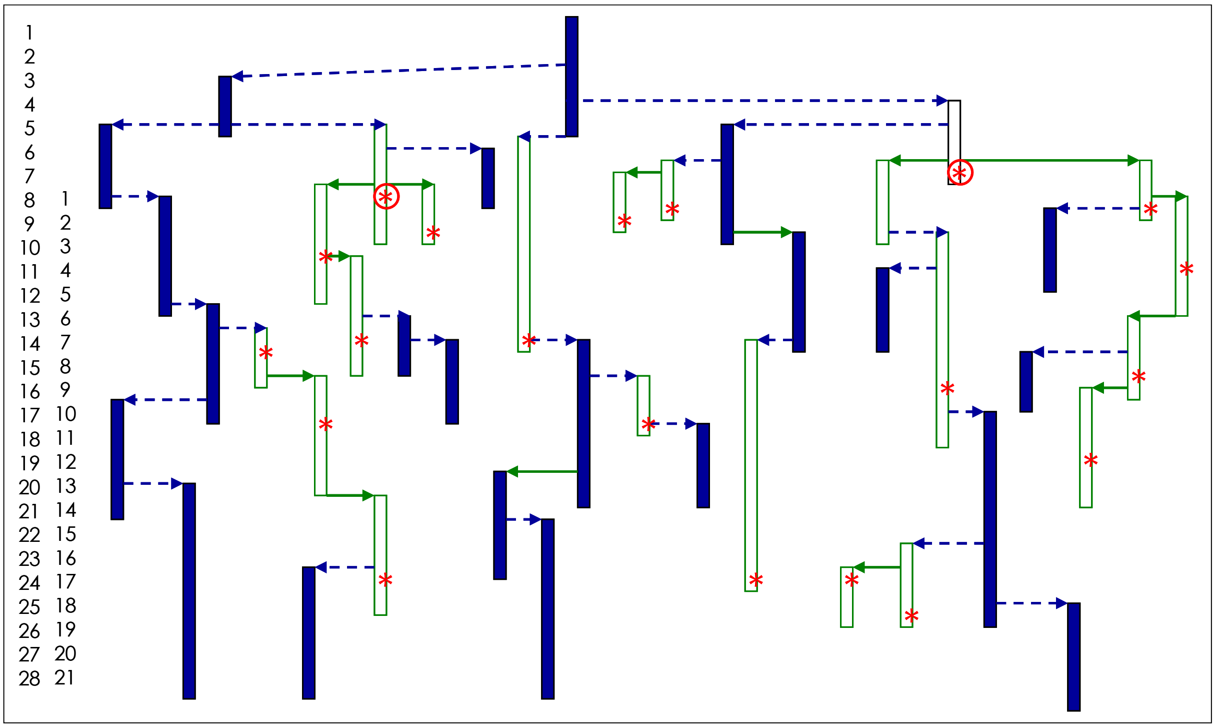

Figure 4
Schematic diagram of disease spread over time illustrating temporal overlap of herds during their respective latent and infectious periods, and the concept of herds known and not known to authorities
Actual time-scale far left
Apparent days of outbreak, inner scale
Hollow green rectangles and solid green arrows represent infected herds and contacts known to authorities
Asterisk illustrates day herd detected, circled asterisks indicate initial detection
Solid blue rectangles and dotted blue arrows represent infected herds and contacts not yet known to authorities

relative date indicated. The solid arrows represent contacts known to authorities. The dotted arrows represent effective transmission contacts that remain as yet unknown to authorities. Note that the true outbreak has been extended over 28 days, but the first discoveries of infected herds (two circled asterisks) were not made until day 8, so the outbreak appears to have lasted for only 21 days.

It is useful to estimate R at different points in time during an outbreak to learn if R is decreasing and if it has been reduced to less than one. It may be estimated by dividing the number of known new cases by the number of known old cases (from the previous incubation period), that would have generated the new cases at the time in question. However, to do so, it is critical to know which infected herds should be classified as new infections, and which are old infections serving as sources for the current new infections. That is, it is critical to know which cases should be included in the numerator and which in the denominator of the estimate of R. This difficulty, combined with the problem of as yet undetected old and new cases (and some herds may even be false-positives), can lead to an incorrect estimate of R. Furthermore, an incorrect estimate of R can lead to inappropriate policy decisions because the outbreak is perceived as being under control (erroneous $R<1$) or out of control (erroneous $R>1$). Therefore, considerable skill, data, knowledge and judgment are required to assess outbreaks (13, 15, 19).

Discussion and conclusion

The disruption of routine flow of trade, caused by serious infectious diseases, such as FMD, is greater in exporting countries that are normally free of such animal diseases. Farm animal workers and owners may perceive themselves as having little influence over the control of diseases that are normally foreign to their country. They may feel dependent on government authorities to protect them from such exotic animal diseases. In addition, people routinely experience competing demands for their time and attention. Examples of such people include animal husbandry-workers, livestock owners, animal health regulatory officials and public policy decision-makers. As such, they do not necessarily have the time or technical skills to study and fully appreciate complex mathematical or computer simulation models. Nevertheless, their decisions and actions are often critical to successful control of animal disease.

The disease spread and control concepts summarised in this paper have all been reported and reviewed previously in more detail, with greater mathematical and epidemiological rigour (1, 2, 3, 11, 12, 16, 18, 21, 25, 27, 30). This paper summarises concepts into simplified models to communicate key principles of infectious disease control to people who do not have time to study more detailed models.

People are more likely to take constructive actions if they honestly believe their personal actions will make a positive difference to people or systems about which they sincerely care. The simple examples, schematic diagrams and equations summarised here are intended to help livestock workers, owners, regulators and policy decision-makers appreciate how their personal day-to-day decisions, actions and systems can greatly influence the size and impact of disease outbreaks on their own farms and on the industry as a whole. This is not only true during official response to known outbreaks, it is also true before the outbreak is known to the authorities, and even before it starts. It is hoped that a broader appreciation of key principles summarised here will compel stakeholders to act routinely in a manner that improves the prevention and control of infectious animal diseases.

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