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PERSPECTIVE

Defining and testing a wildlife intervention framework for exotic disease control

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Abstract

1. Outbreaks of disease at the wildlife–livestock interface may require management interventions. Where they involve exotic/non-endemic pathogens in wildlife, then such plans may need to be rapidly conceived and implemented to prevent further disease spread. However, detailed information on the distribution of infection is likely to be absent, whilst limited resources and tools, and ethical considerations impose constraints on what is possible and proportionate.
2. We describe four considerations to inform decision-making on whether to intervene. With reference to two recent examples (bovine tuberculosis in badgers in an otherwise disease-free area, and African swine fever in wild boar in central Europe), we outline six steps to guide implementation.
3. In both examples, a Disease Control Area was defined by determining a minimum infected area (MIA) and a buffer zone based on wildlife ecology and the potential for unrecorded spread of infection. The total area was the subject of management intervention, with the level of infection used to inform adaptive management.
4. The MIA is defined as the minimum area that *could* contain all infected wildlife, given our current level of information, with a surrounding buffer zone to account for the possibility of further onward spread. In our examples, the zones were defined using a combination of field data and existing knowledge of host spatial organization and movement.
5. The MIA (plus buffer zone) approach provides a framework for optimizing the targeting of resources in a proportionate response to a disease outbreak. Where infected animals occur outside the MIA, our examples show how wildlife management has been adapted. In principle, this approach is suitable for the delivery of disease outbreak control in wildlife, whether through culling, vaccination or other forms of control.

KEYWORDS
ASF, badger, bovine TB, disease control, outbreak response, wild boar, wildlife management

1 | INTRODUCTION

While there are many diseases of wildlife, only a few pose significant risks to human health or well-being and hence merit intervention (Delahay et al., 2009). In Europe, several important diseases are shared between wildlife and livestock, particularly affecting wild suids, cervids, carnivores and birds (Gortazar et al., 2007). For example, bovine tuberculosis (bTB; caused by *Mycobacterium bovis*) costs the U.K. Government up to £100 million per annum (Defra, 2013) and the spread of African swine fever (ASF) into Romania in 2018 resulted in the slaughter of over 300,000 domestic pigs (Stancu, 2018). Control of bTB in cattle in the United Kingdom and Ireland is hampered by infection in wild badgers *Meles meles*, while domestic pig populations in Europe are threatened by the westward spread of ASF in wild boar *Sus scrofa* (EFSA Panel on Animal Health and Welfare et al., 2018).

Where outbreaks occur in domestic animals and wildlife due to the introduction of a pathogen into a previously uninfected area, prompt action may be required to eliminate disease, and this is often embodied in contingency planning (Jackson et al., 2009). In outbreak situations, the need to act quickly may require decisions to be taken based on incomplete data and with only limited planning and tools available, whilst the availability of resources and ethical considerations impose the need to act proportionately. Ethical and economic considerations will likely constrain the size of any intervention (particularly if culling is employed), while risk mitigation and fear of failure to contain disease will tend to enlarge any intervention zone. Consequently, policy options in such circumstances are inevitably constrained.

Based on our joint experience, we have identified a number of principles to maximize the likelihood of successful elimination of a focus of infection involving wildlife. Before any wildlife intervention starts, four initial considerations are recommended: Confirm, Clarify, Resource and Exit. That is, (a) confirm that wildlife species are likely to constitute maintenance hosts, (b) clarify the overall objective (disease elimination, containment or mitigation), (c) ensure sufficient resources are available to achieve the desired goal and (d) identify the exit requirements for disease elimination. Intervention is often started without full consideration of this last step due to the perceived need to do 'something', and where not explicitly stated in international protocols will depend on risk appetite and the consequences of undetected infection as determined by the policy maker. Declaration of disease-free status should be based on international standards set by OIE, WHO or FAO where this is possible (e.g. for ASF the criteria are described in Article 15.1.4 of the OIE Terrestrial Animal Health Code: https://www.oie.int/index.php?id=169&L=0&htmfile=chapitre_asf.htm).

Once these considerations have been addressed, intervention may be deemed appropriate, and planning can proceed. Here, we describe two examples where local disease eradication in wildlife was instigated through six steps. The concept of the minimum area that may contain all infected animals (minimum infected area [MIA]) and a buffer zone to account for undetected spread became central to both examples and represents an efficient mean to target resources and apply proportionality.

2 | CASE STUDY 1: BOVINE TUBERCULOSIS FOCAL OUTBREAK

In parts of the United Kingdom, bTB transmission occurs amongst cattle and local badgers. Badgers are likely to be maintenance hosts since R0 is greater than unity and sustained within-species transmission could occur in an area of endemic infection (Crispell et al., 2019; Delahay et al., 2013). For the purposes of disease management, England is split into zones of high, intermediate and low bTB risk. Recently bTB was also detected in badgers in part of the low-risk area, concurrent with infection in cattle. The *M. bovis* genotype (17:z) associated with that outbreak indicated that it had been introduced through importation of cattle from Northern Ireland (Defra, 2018b). Since the government strategy is to achieve disease freedom by 2038 (Defra, 2020a), any response would essentially be similar to that employed during an exotic disease outbreak. Enhanced cattle surveillance measures were also put in place, but we report here on the wildlife response.

2.1 | Step 1: Initial surveillance

A cluster of bTB breakdowns in cattle farms in Cumbria, starting in 2014, led to identification of a 250-km^2 hotspot with enhanced bTB surveillance in cattle and wildlife in September 2016 (Defra, 2018b). Of 35 badgers found dead by early 2018, three were infected with an identical *M. bovis* genotype to that found in the local cattle. Whole-genome sequencing (WGS) revealed three different sequences in the badgers, only one of which had been found in the cattle, indicating a high likelihood of within-species transmission. Field veterinary investigations indicated that some of the herd breakdowns were not due to importation or other routes of cattle-to-cattle spread and were thus likely to be from wildlife. The available evidence indicated the potential for badgers to act as a maintenance host in the Cumbria hotspot, and U.K. Government policy is to eradicate bTB in the low-risk area (Defra, 2013), which satisfies requirements (a) to (c). Since local bTB eradication has not previously been achieved in badgers, requirement (d)—determining disease freedom—would have to be formulated during the outbreak response.

2.2 | Step 2: Define the MIA

Following confirmation of steps (a) to (d) and confirmed transmission between cattle and badgers, the MIA was defined. Badgers are group-living and main setts (their larger burrow systems) serve as a useful proxy for the number of groups (see Judge et al., 2014), each of which will occupy a territory. Estimated badger main sett density (Judge et al., 2014) was used to map a target area for a field survey for main setts. Veterinary investigations identified where infected cattle had been since the last time they were tested. This permitted the land within each infected farm to be assigned a categorical risk of

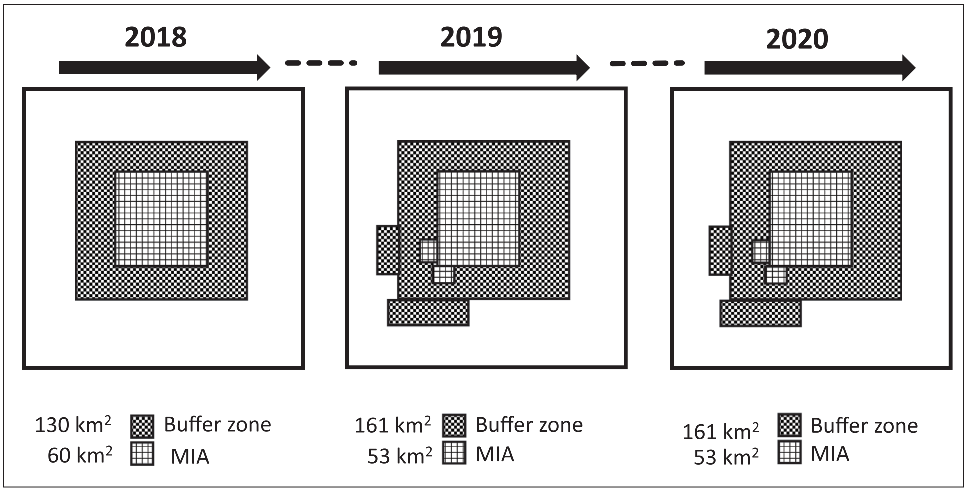

FIGURE 1 Temporal evolution of the zoning strategy applied to control bovine TB in Cumbria, England, along with approximate sizes for the MIA (minimum infected area) and buffer zone for each year. Exact geographic detail has been excluded to ensure anonymity.

cattle–wildlife interaction. Grazing land and cattle housing assessed as high or medium risk were mapped to the local overlapping badger territories. The MIA was defined by producing a single contiguous area containing the badger territories that overlapped the location of the three bTB confirmed badgers, and those that overlapped high- and medium-risk farmland. The MIA was ~60 km^2 and contained an estimated 40 badger territories.

2.3 | Step 3: Buffer the MIA

As bTB was introduced to the area some time prior to the first recorded outbreak in November 2014, initial spill over to badgers may have been prior to detection in cattle. We cannot know how many times infection had spread from cattle to badgers within the area, nor how often this led to onward transmission. Field experience elsewhere, preliminary modelling, and the observation that most badger movements in undisturbed populations tend to be amongst neighbouring groups (Macdonald et al., 2008; Rogers et al., 1998), suggested that infection would spread slowly and so a buffer of two badger territories would be likely to encompass all onward transmission beyond the established MIA. Where possible, the boundary of this buffer was delineated to correspond with features such as rivers, railway lines or major roads where these were assessed to correspond to territory edges. In the south-west of the area, it was not necessary to have an extensive buffer as an expanse of moorland provided generally unsuitable habitat for badgers. Following review, the finalized MIA was defined (Figure 1).

2.4 | Step 4: Define the method of control

There was no evidence to support badger management outside the defined buffer, and it was possible that all infected badgers would be inside the MIA. Government policy for controlling bTB in badgers in endemic areas involved issuing licences to local landowners to permit badger culling by trapping and/or shooting. Consistent with this, during 2018 local farmers and landowners were invited to apply for a licence to cull badgers in the delineated area in Cumbria. Badger vaccination is available but was not considered suitable as the first line of control due to the expected slower rate of disease reduction (Smith et al., 2012).

2.5 | Step 5: Implement

Following granting of a licence, in September 2018, badger removal was initiated (Defra, 2018a) resulting in 602 animals being culled. Of these, 363 were suitable for post-mortem examination, of which 41 (11.3%) were infected (Defra, 2019). Thirty-eight of these infected badgers originated from within the MIA (21% prevalence), and only three from within the buffer (2% prevalence).

2.6 | Step 6: Measure and adapt

The locations of all positive badgers, and further cattle herd breakdowns with a high risk of badger involvement, were used to re-define the MIA and the buffer zone for subsequent culling operations. In 2019, the MIA was enlarged to the west to include the locations of the three positive badgers found in the buffer, and reduced to the east where no confirmation of infection was found. The buffer was also enlarged westward to maintain a similar boundary distance. Ongoing herd breakdowns may also risk further spread from cattle to badgers, as genetic evidence indicated that there were multiple transmissions from cattle to badgers (Rossi et al., 2022). During the 2019 badger control operation, two of the 313 badgers removed were positive for *M. bovis* genotype 17:z (overall prevalence 0.6%) and both originated from within the revised MIA (Defra, 2020b). For 2020, the control operation was then adapted to consist of a central cull area where positive badgers were found, and a surrounding badger vaccination zone in the outer buffer where no positive badgers had been found during the previous 2 years of culling. In 2020, a total of 100 badgers were vaccinated in the outer buffer and 133 were culled in the MIA. No culled badgers were positive for *M. bovis*; therefore, for the first time the prevalence was estimated at zero from the sampled animals (Defra, 2021). Given the chronic nature of bTB and the potential for infected animals to survive for several years (Graham et al., 2013), it is unlikely that local disease elimination will be confirmed for a number of years. In this case, no formal exit strategy has been agreed in advance due to the difficulty of determining if an outbreak in cattle was caused by badgers.

3 | CASE STUDY 2: ASF FOCAL OUTBREAK

Wild boar are confirmed maintenance hosts for ASF (EFSA Panel on Animal Health and Welfare et al., 2018). Endemic management has not achieved disease elimination, but due to the risk of economic damage any remote focal outbreak would first be subjected to an elimination attempt. Without previous experience of successful control, a formal exit strategy was not defined at the start.

3.1 | Step 1: Initial surveillance

ASF has recently spread in wild boar populations across parts of eastern Europe, and in June 2017 it was first identified in the Czech Republic in a dead wild boar following a long-distance human-mediated translocation (EFSA Panel on Animal Health and Welfare et al., 2018). Surveillance for infection in wild boar allowed an infected area to be defined and a series of measures were implemented, including increased biosecurity on domestic pig farms (EFSA Panel on Animal Health and Welfare et al., 2018).

3.2 | Step 2: Define the MIA

A provisional infected area of 10-km diameter was established ad hoc by the State Veterinary Administration (SVA) around the first confirmed case of ASF in wild boar as an immediate response. Six days later, a definitive 'officially infected area' of 1003 km^2 (42% forest and 46% agricultural land, with 187 inhabitants/km^2), within administrative unit district Zlín, was established in accordance with EU guidance (Commission Implementing Decision [EU] 2017/1162) and following the recommendation of the ASF crisis management group (CMG) established by the Chief Veterinary Officer. The CMG included representatives of the SVA, State Veterinary Institute (NRL for ASF), Ministry of Agriculture, Army Veterinary Services, veterinary and wildlife scientists, animal carcass-rendering companies and non-governmental organizations (hunting association, pig farming association). The CMG maintained close contact with the local authorities, local hunting clubs and farmers. A ban of all hunting activity (to reduce risks of emigration due to disturbance), and active carcass search and removal operations (to remove infectious carcasses) coordinated by the SVA and local hunters, was initiated over the entire 1003 km^2. During the first 3 weeks, a thorough search of the entire 'officially infected area' revealed 79 wild boar carcasses, 59 (75%) of which were ASF positive. All positive carcasses originated from an area of only 13 km^2. Based on published data on wild boar space use and the restricted distribution of infected cases, it was initially assumed that infection had not escaped outside of a focal area. The MIA was then defined based on the focal area enclosed by the natural or anthropogenic barriers which were likely to encompass the ranging behaviour of any boar that could be infected (total size of 57.2 km^2).

3.3 | Step 3: Buffer the MIA

The SVA set up a zoning management system around the MIA (Figure 2). The buffer zone around the MIA represented the annual size of a wild boar home range based on published data (i.e. 2500 ha), considering the landscape and administrative hunting units (EFSA, 2018). The high-risk area (HRA; i.e. MIA + buffer zone) covered approximately 89 km^2 (9%) of the whole officially infected area. The remainder was a low-risk area (LRA) covering 914 km^2. In this example, because of the rapid spread of ASF previously observed in wild boar in the Baltic region, a larger intensive hunting area (IHA) was established (8500 km^2) to reduce population size around the infected area.

3.4 | Step 4: Define the method of control

Control aimed to (i) minimize movement of wild boar between the MIA and the surrounding area by banning all hunting activity in the MIA during the early epidemic stage of the outbreak and where appropriate by using mechanical barriers (fences and existing infrastructure), (ii) reduce potential sources of ASF virus inside the MIA by safe carcass removal and (iii) minimize environmental contamination through increased hunting biosecurity when hunting was re-established in the HRA (e.g. hunting was only carried out by trained hunters, and all carcasses were marked and securely stored in plastic boxes for removal to a rendering plant). The movement mitigation strategy was designed to reduce outward movement from the MIA (see Cromsigt et al., 2013). After confirmation of the first positive case, all hunting activities (individual and driven hunting, baiting, feeding, dog training etc.) were banned (following EC Implementing Decision [EU] 2017/1162) for periods of 5 (LRA) and 10 (HRA) weeks to minimize disturbance. With no suitable vaccine available, subsequent control of ASF would be conducted by high-intensity organized wild boar culling with biosecurity measures and carcass removal in the infected area.

3.5 | Step 5: Implement

Different hunting regimes were implemented. In the HRA, low-intensity hunting of boar (maximum of three hunters per hunting

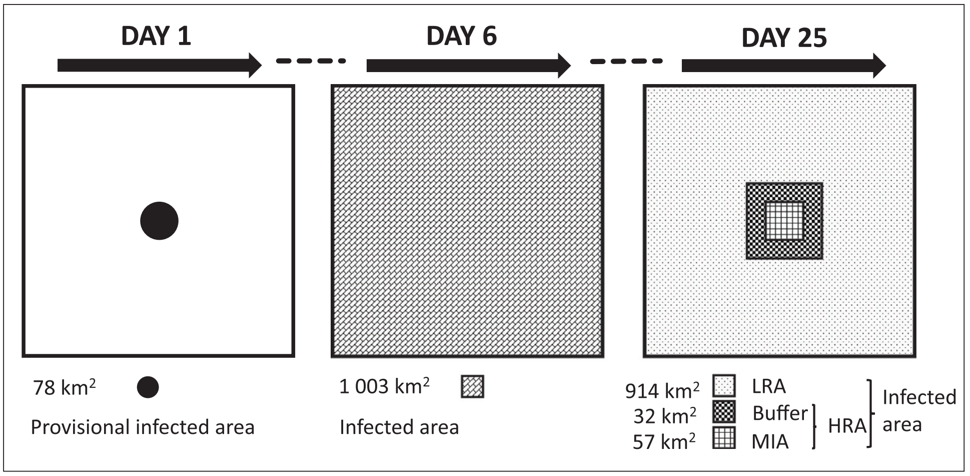

FIGURE 2 Temporal evolution of the zoning strategy applied to control ASF epidemic in Czech Republic. LRA, low-risk area; HRA, high-risk area; MIA, minimum infected area. See the text for description of measures implemented in each zone. Level of detail matched to Figure 1

ground alternating shooting locations every week) was organized by the state administration and implemented by local hunters and police snipers. In the LRA, hunting also took place without restrictions on the number and spatial distribution of hunters. In the larger IHA, boar were hunted individually and in groups (i.e. driven) without any restrictions. To limit wild boar movements out of the MIA, the area was partly fenced with electric and odour fences and public access prohibited, whilst food availability and shelter within the HRA were increased by suspending crop harvesting. To reduce the environmental viral load, hunters searched for wild boar carcasses which were subsequently removed by the SVA. At the end of the epidemic, systematic searches for wild boar carcasses were conducted in the entire HRA and LRA. A high level of biosecurity was applied in the HRA and LRA, including designated sites for carcass storage, obligatory testing and disposal of all found and hunted boar in rendering plants and biosecurity training for hunters. All these activities were financially subsidized by the SVA or Ministry of Agriculture.

3.6 | Step 6: Measure and adapt

Surveillance data were continuously collected and evaluated, and the efficacy of control was evaluated on a regular basis by the CMG, based on disease surveillance data and wild boar population monitoring. Consequently, some measures were cancelled or introduced during the control programme as adaptive responses, while the size of the control zones remained constant throughout the outbreak. These included the decision to depopulate the MIA using police snipers taken at the end of the epidemic phase (zero cases detected in a week) in October 2017, the intensive searches for carcasses to confirm absence of ASF-positive animals in April 2018 and the removal of electric and odour fences in October 2018. Throughout the outbreak period (June 2017 to April 2018), 268 boar were found dead and 279 were shot within the MIA. Field observations (camera trapping, thermal aerial survey, signs of presence) suggested that by April 2018 there were probably no boar left in the MIA. In total, from June 2017 to April 2018, 212 ASF-positive boar were found dead and 18 had been killed by snipers and hunters. Of these 230 cases, 221 were inside the original MIA. The last ASF-positive wild boar was found 292 days after the first. Just nine positive cases were located immediately outside the MIA (but still within the HRA) and probably belonged to a family group which emigrated from the MIA. Intensive carcass searches during April 2018 provided no evidence of an outbreak and confirmed the assumption that there was no risk of further spread of ASF. After 10 months had elapsed since the last case of ASF in wild boar, all restrictions in the Czech Republic were lifted (European Commission, 2019) and the country was declared ASF free in April 2019.

4 | DISCUSSION

Others have proposed various steps that should be taken prior to a culling intervention (Miguel et al., 2020), but our suggestions here are applicable to a range of interventions, and importantly rely on adaptive management to monitor and adjust the whole program in the light of the emerging evidence. Any such intervention should be science based and adaptive (Vicente et al., 2019), which requires a greater emphasis on data collection, wider data sharing and enhanced cooperation (Blackburn et al., 2016). Both case studies outlined here describe a similar sequence of operational steps to control an outbreak of an exotic/non-endemic pathogen in wildlife that we summarize below as a generic recommendation. In both cases, disease elimination has not been previously achieved for these host/pathogen combinations. In the ASF example, a larger IHA was established to further reduce the risk of disease spread. Such additional measures may be necessary where there is a lack of experience and the consequences of disease spread substantial. Four initial preparatory considerations—Confirm, Clarify, Resource and Exit—should be implemented before action is taken: Confirm the species is a likely reservoir, Clarify the objective, ensure sufficient Resource and discuss and agree the Exit strategy (i.e. define success). Following this, a six-step programme of action should be initiated. This involves:

1. Rapid collation of epidemiological surveillance data and its combination with ecological information on the wildlife host to
2. Identify an MIA with
3. A surrounding buffer to account for uncertainty and potential natural and management-induced movements of the host. These areas are inevitably a compromise borne out of the need to act quickly and the availability of imperfect information.
4. The intervention measures employed in the target areas will depend on the objectives, the characteristics of the pathogen and the host population, but could include combinations of fencing, culling, selective removal (e.g. on the basis of a diagnostic test result) and vaccination depending on what tools are available. Where the over-arching purpose is to prevent infection of livestock, contemporaneous disease management in both the wild and domestic animal populations will be required.
5. During the implementation of disease control measures, all epidemiological and ecological data should continue to be collected to
6. inform ongoing adaptive management and the identification of an end point: successful eradication or a switch to mitigation.

Using the approach described here, disease elimination in wildlife has been confirmed in the case of ASF in wild boar in the Czech Republic, but for bTB control in badgers in a non-endemic area of the United Kingdom, confirmation of disease freedom will take longer, although clear evidence already exists to show a dramatic reduction in prevalence to near zero. This approach was also used during an ASF outbreak in Belgium, which was subsequently declared disease free (FASFC, 2020). Therefore, the principles for maximizing the likelihood of a successful intervention and the practical steps for its implementation described here provide a useful framework for planning and managing such outbreaks.

AUTHOR CONTRIBUTIONS

Graham Smith conceived the overall idea and produced a first draft of the manuscript. Tanis Brough provided further details on the first case study. Tomasz Podgórski, Milos Ježek, Petr Šatrán and Petr Vaclavek provided the second case study. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

This work does not contain any original data.

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