

ORIGINAL RESEARCH

The Cull as a Source of Exposure: Ring Culling Radius, Epidemic Size and Human Contact with Poultry in Avian Influenza Control

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Abstract

Background. Highly pathogenic avian influenza is controlled by depopulating infected flocks and, in most schemes, all flocks within a radius of them. Depopulation is also among the highest-risk human exposures to these viruses, so the control measure generates part of the contact it exists to prevent. We asked where the radius that minimises human exposure lies.

Methods. We simulated between-flock spread across 260 poultry holdings in a 40-kilometre square with a distance-based transmission kernel, detection delay and ring culling at radii from 0 to 8 km, over 300 replicate epidemics per radius. Human exposure was accumulated as hazard-weighted person-days across three sources: depopulating infected flocks, depopulating uninfected ring flocks, and ordinary husbandry on flocks still in production.

Results. Without ring culling, epidemics reached 17.0 flocks and generated 1161 hazard-weighted person-days of exposure. A 2 km ring reduced infected flocks to 5.8 while culling 85,644 fewer birds in total, so both poultry losses and human exposure fell. Beyond that the trade reversed: at 4 km each additional flock infection averted cost 9,091 birds culled and at 8 km 40,073, while infected flocks fell only from 5.8 to 2.5. The composition of exposure inverted, with uninfected flocks accounting for 16 per cent of depopulation-related exposure at 2 km and 70 per cent at 8 km. The radius minimising total exposure depended on the assumed hazard of depopulating an uninfected flock, moving from 8 km at a relative hazard of 0.02 to 4 km at 0.50.

Conclusion. A small ring reduced both poultry destruction and human exposure. Wider rings bought little further epidemiological benefit at rapidly rising cost, and the optimum turned on a hazard weight that is not measured.

Keywords: avian influenza; ring culling; agricultural occupational health; zoonotic disease; poultry; One Health interface.

1. Introduction

Highly pathogenic avian influenza has become a recurrent emergency in commercial poultry production, with successive panzootics causing the destruction of hundreds of millions of birds [1-3]. The standard response is stamping out: infected flocks are depopulated, and in most national schemes so are all flocks within a defined radius, on the grounds that they are likely to have been exposed and will otherwise seed further spread [4,5].

The same viruses cause severe human disease, and the human cases that occur are overwhelmingly in people with direct, sustained contact with poultry [6-8]. Among those exposures, depopulation of an infected flock is the most intense: it involves prolonged close handling of large numbers of birds in an enclosed space with high viral loads and substantial aerosol generation [9,10].

A ring culling policy therefore acts on human risk in two opposite directions. By removing susceptible hosts it shortens the epidemic and reduces the number of infected flocks that will ever need depopulating. By widening the ring it requires teams to depopulate a larger number of flocks, most of them uninfected, and so puts more people into contact with more poultry.

The two effects are not symmetric in hazard. Depopulating an infected flock carries a far higher risk of human infection than depopulating an uninfected one, and how much higher is not well characterised. That ratio, rather than the epidemiology, may determine where the best radius lies.

Policy debate on culling radius has focused almost entirely on epidemic control and on the economic cost of poultry destroyed [11-13]. We add the human exposure that the operation itself generates and ask how it changes the answer.

1.1 Objectives

We aimed to quantify epidemic size, poultry destroyed and human exposure as functions of the ring culling radius; to determine the radius at which each is smallest; to establish the cost in birds of each flock infection averted; and to test how far the conclusion depends on the assumed hazard of depopulating uninfected flocks.

2. Materials and Methods

2.1 Landscape and transmission

We simulated 260 poultry holdings distributed at random across a 40-kilometre square, with flock sizes drawn lognormally about a mean of 22,000 birds. Between-flock transmission followed a distance kernel of the form

$$k(d) = \alpha / [1 + (d/h)^2] \quad (1)$$

which declines steeply with distance while retaining a tail, consistent with kernels estimated from historical outbreaks in which most spread is local but occasional long jumps occur.

Flocks passed through a latent period before becoming infectious, and an infectious flock was detected after a further delay, representing the interval between infection and recognition of clinical signs and laboratory confirmation. On detection, the flock was depopulated together with all flocks within the ring radius. 300 epidemics were simulated per radius.

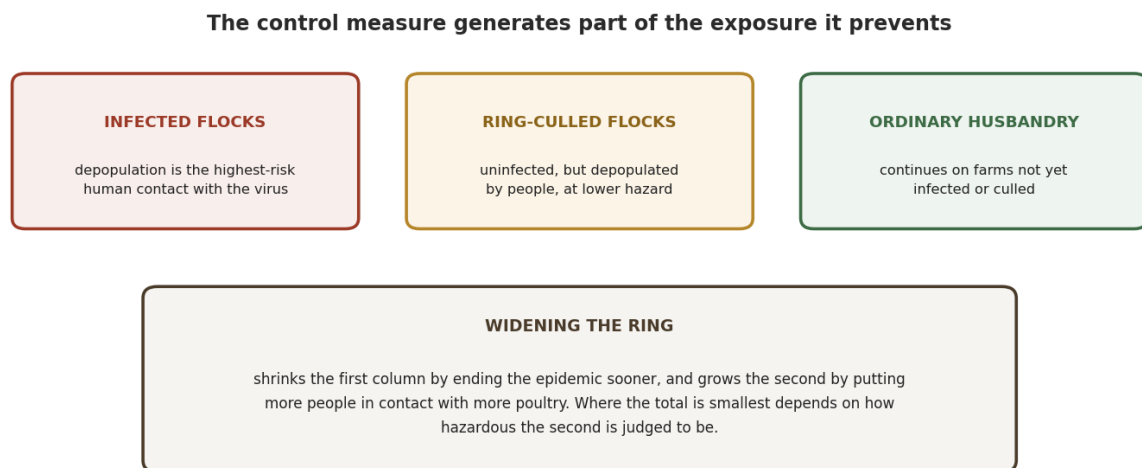


Figure 1. The three sources of human contact with poultry and how the ring radius changes their balance.

2.2 Human exposure

Human exposure was accumulated in hazard-weighted person-days from three sources. Depopulation generates person-days in proportion to the number of birds handled. Those person-days carry a relative hazard of 1 when the flock is infected and a much lower weight when it is not, since an uninfected flock presents ordinary occupational risk rather than exposure to the virus. Ordinary husbandry on flocks still in production carries a small weight, representing the background contact that exists whether or not there is an epidemic.

The base-case relative hazard for depopulating an uninfected flock was 0.12, and this assumption is varied across two orders of magnitude in Section 3.5 because it is the least well established quantity in the model.

Parameters are given in Table 1. All are illustrative and represent a commercial poultry landscape rather than a specific country or outbreak.

Table 1. Model parameters.

Parameter	Value	Note
Holdings	260 in a 40 km square	Commercial density
Flock size	Lognormal, mean 22,000 birds	Spans small to very large units
Transmission kernel	$\alpha/(1+(d/h)^2)$, $h = 2.1$ km	Local spread with a long tail
Latent period	3 days	Infection to infectiousness
Detection delay	5 days	Infectiousness to confirmation
Ring radii	0 to 8 km	Spanning schemes in current use
Depopulation exposure	0.85 person-days per 1000 birds	Team size and duration
Relative hazard, uninfected flock	0.12	Varied from 0.02 to 0.50
Relative hazard, routine husbandry	0.04	Background contact
Replicate epidemics	300 per radius	Per configuration

3. Results

3.1 Epidemic size and poultry destroyed

Table 2 and Figure 2 give the epidemiological outcome. Without ring culling, epidemics reached 17.0 flocks on average and lasted 36 days, with 439,460 birds destroyed, all of them from infected flocks.

A 1 km ring reduced infected flocks to 12.1 and a 2 km ring to 5.8. Beyond 2 km the epidemiological return diminished sharply: 4 km gave 4.0 infected flocks and 8 km gave 2.5.

Total birds destroyed behaved differently. It fell from 439,460 with no ring to 353,816 at 2 km, because containing the epidemic early saved more infected flocks than the ring destroyed. It then rose, to 558,040 at 4 km and 1,021,191 at 8 km, as preemptive destruction outgrew the infections avoided.

The turning point is the substantive result of this section. Up to about 2 km, ring culling is not a trade at all: fewer flocks are infected and fewer birds are destroyed. Beyond it, further widening purchases small epidemiological gains with large and rising poultry losses.

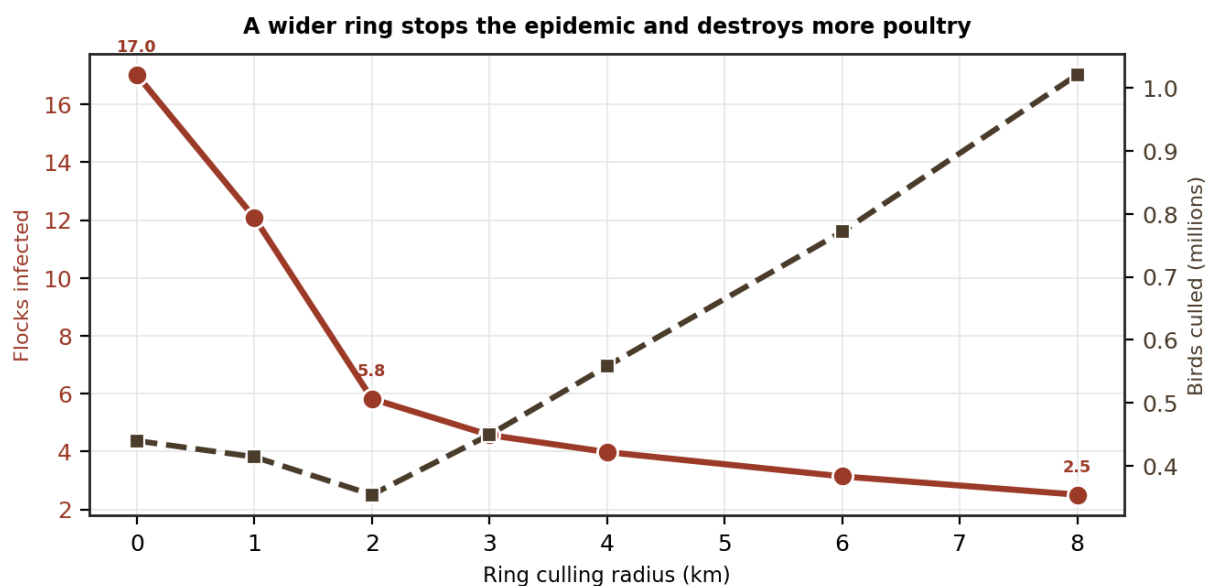


Figure 2. Flocks infected and birds destroyed against ring culling radius.

Table 2. Epidemic outcome by ring radius.

Radius (km)	Flocks infected	Flocks culled	Birds culled	90th percentile flocks infected	Duration (days)
0.0	17.0	17.0	439,460	63	36
1.0	12.1	16.2	413,845	42	30
2.0	5.8	13.8	353,816	14	20
3.0	4.6	17.7	448,935	12	18
4.0	4.0	22.0	558,040	9	15
6.0	3.1	30.2	771,626	7	13
8.0	2.5	39.9	1,021,191	5	11

3.2 The efficiency of each additional kilometre

Table 3 and Figure 3 express the same data as a cost per flock infection averted, relative to no ring culling.

At 1 and 2 km the figure is negative: the policy averted 11.2 flock infections at 2 km while destroying 85,644 fewer birds overall. At 3 km it turned positive at 761 birds per infection averted, rising to 9,091 at 4 km and 40,073 at 8 km.

The escalation is steep because the two quantities move in opposite directions with radius. The number of flocks available to be infected falls as the ring grows, so each further kilometre averts fewer infections, while the area enclosed grows with the square of the radius, so each further kilometre destroys more flocks. The ratio therefore rises faster than either term alone.

A policy set at 8 km in this landscape would be destroying on the order of forty thousand birds for each flock infection it prevents, which is a figure that ought to be stated when such a radius is chosen.

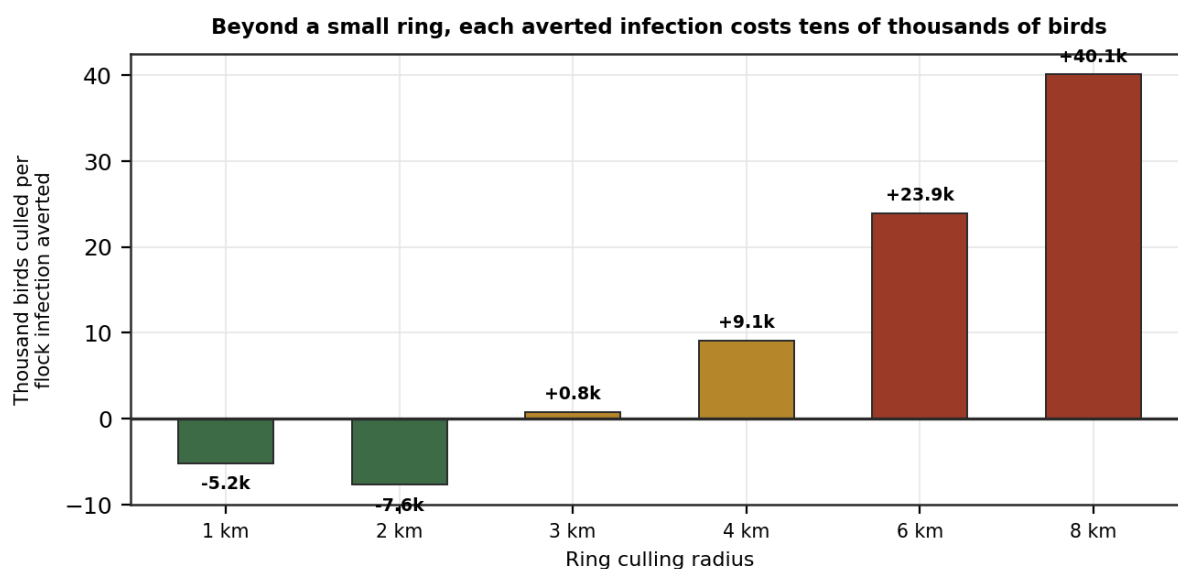


Figure 3. Birds destroyed per flock infection averted, relative to no ring culling.

Table 3. Cost of each flock infection averted.

Radius (km)	Flock infections averted	Additional birds destroyed	Birds per infection averted
1.0	4.9	-25,615	-5,189
2.0	11.2	-85,644	-7,647
3.0	12.5	+9,475	+761
4.0	13.0	+118,580	+9,091
6.0	13.9	+332,166	+23,926
8.0	14.5	+581,731	+40,073

3.3 Human exposure and its composition

Table 4 and Figure 4 give hazard-weighted human exposure. Total exposure fell with radius across the whole range tested, from 1161 person-days with no ring to 396 at 8 km, because the dominant term — contact with infected flocks and with flocks still in production during a long epidemic — falls as the outbreak is contained.

The composition changed markedly. Exposure from depopulating infected flocks fell from 374 to 42 person-days, while exposure from depopulating uninfected ring flocks rose from zero to 99. Among depopulation-related exposure specifically, uninfected flocks accounted for 16 per cent at 2 km and 70 per cent at 8 km.

So while wider rings reduced total exposure under the base-case weighting, they progressively shifted its source from the disease to the control measure. By 8 km, most of the depopulation

work being done, and most of the person-days generated by it, involved flocks that were never infected.

We want to be careful about what this does and does not show. It does not show that wide ring culling increases human risk under our base-case assumptions; it does not. It shows that the margin by which it reduces risk depends increasingly on a hazard weight for uninfected-flock depopulation that is assumed rather than measured, and Section 3.5 examines what happens when that assumption changes.

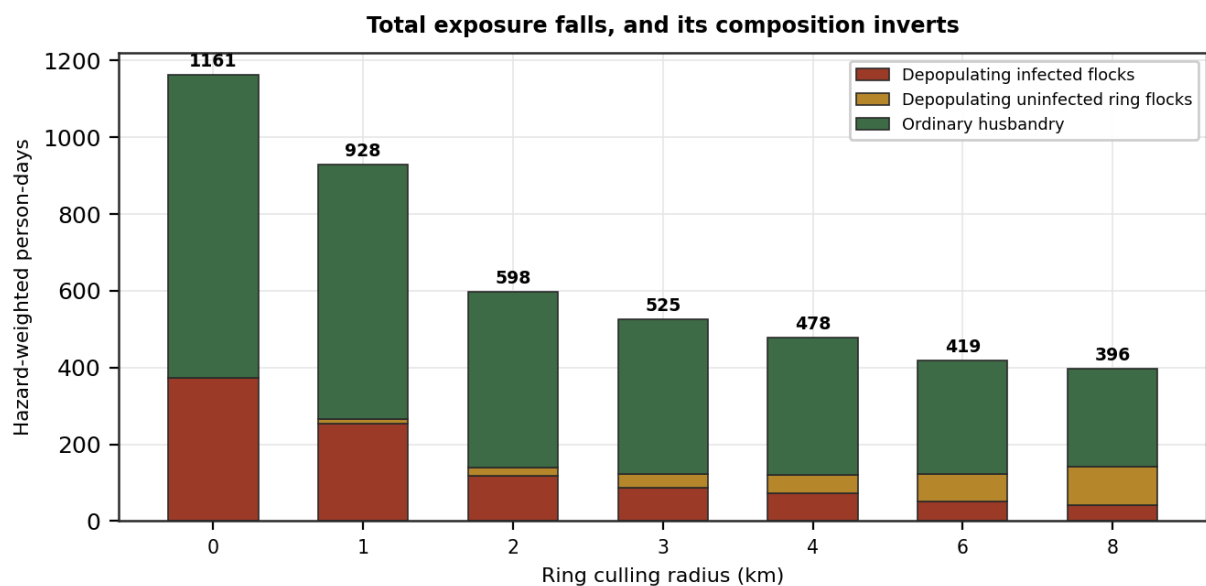


Figure 4. Hazard-weighted human exposure by source and ring radius.

Table 4. Human exposure by source.

Radius (km)	Infected flock depopulation	Uninfected flock depopulation	Ordinary husbandry	Total	Uninfected share of cull exposure
0.0	373.5	0.0	787.4	1161.0	0%
1.0	254.7	11.7	661.8	928.1	4%
2.0	117.8	21.9	458.1	597.9	16%
3.0	87.8	35.3	402.2	525.3	29%
4.0	73.0	48.2	356.4	477.6	40%
6.0	51.0	72.6	295.1	418.7	59%
8.0	42.1	99.1	254.6	395.8	70%

Hazard-weighted person-days. Weights: infected flock depopulation 1.00, uninfected flock depopulation 0.12, ordinary husbandry 0.04.

3.4 Two objectives, one radius

In the base case the radius minimising flocks infected and the radius minimising human exposure coincided, both at 8 km. That is a convenient result and it is specific to the weighting used.

It arises because the epidemic-control term dominates: containing the outbreak removes not only infected-flock depopulation but also the prolonged ordinary husbandry exposure of a long epidemic, which at no ring culling accounted for 787 of 1161 person-days.

The convenience should not be mistaken for a general finding. The two objectives coincide here because uninfected-flock depopulation was assigned a low hazard. Where that assumption is relaxed, they separate, as the next section shows.

3.5 Everything turns on an unmeasured weight

Table 5 and Figures 5 and 6 vary the relative hazard of depopulating an uninfected flock from 0.02 to 0.50, a factor of 25.

The radius minimising total human exposure moved from 8 km at the lowest weight to 4 km at the highest. The benefit over no ring culling also fell, from 73.0 per cent to 45.7 per cent.

The weight is a quantity about which little is known. It represents how much of the human infection risk of a depopulation operation comes from the virus in the flock rather than from the operation itself — the dust, the handling, the confined space, the fatigue and the protective equipment worn imperfectly for long shifts. Serological studies of cullers exist but are not designed to separate these components [14,15].

Our point is not that the weight is high. It is that the policy recommendation is sensitive to it across the plausible range, that this sensitivity is not usually acknowledged when a radius is specified, and that the studies which would resolve it would not be difficult to design: serological follow-up of depopulation teams, stratified by whether the flocks they handled were subsequently confirmed infected.

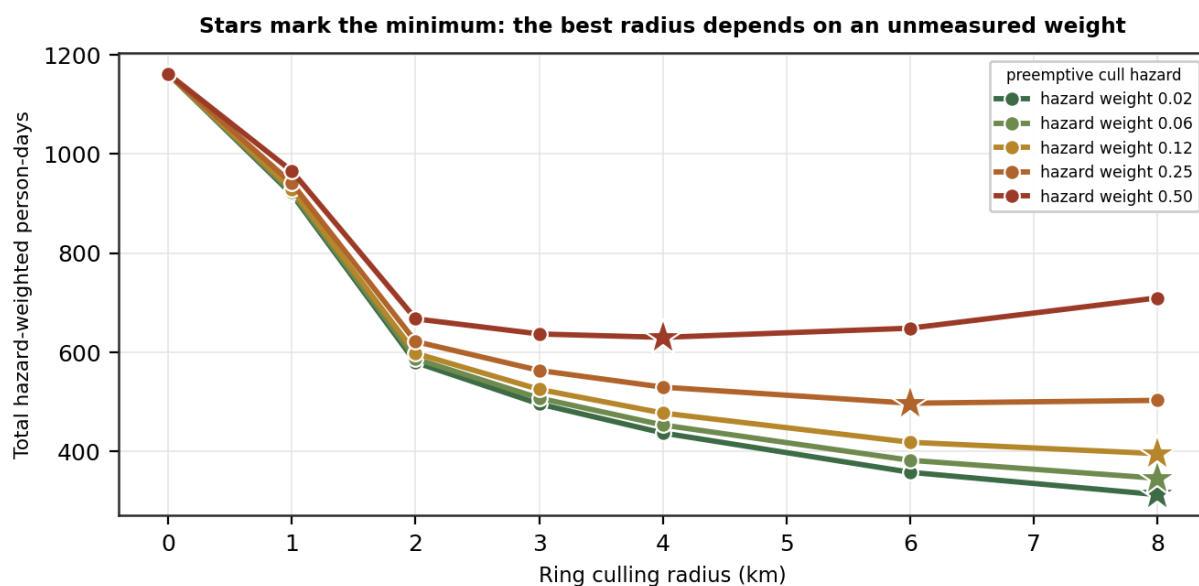


Figure 5. Total exposure against radius under five assumptions about the hazard of uninfected-flock depopulation.

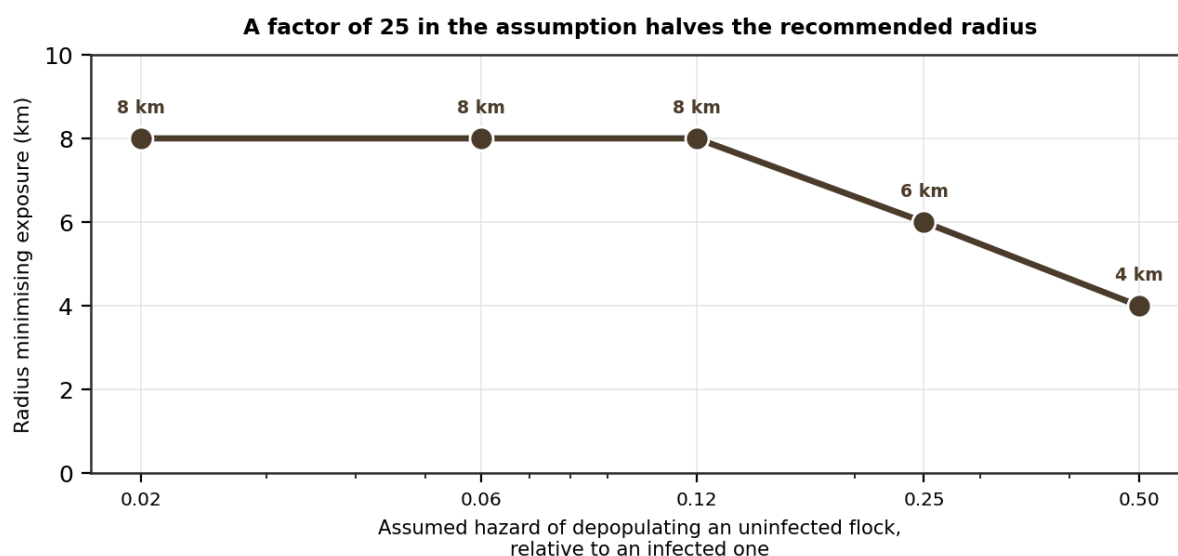


Figure 6. Exposure-minimising radius against the assumed hazard weight.

Table 5. Sensitivity of the optimal radius to the assumed hazard weight.

Relative hazard of uninfected flock depopulation	Exposure-minimising radius (km)	Exposure at that radius (person-days)	Reduction against no ring culling
0.02	8.0	313.2	73.0%
0.06	8.0	346.2	70.2%
0.12	8.0	395.8	65.9%
0.25	6.0	497.4	57.2%
0.50	4.0	630.1	45.7%

Table 6. What each radius band achieves.

Radius band	Epidemiological effect	Poultry cost	Human exposure
0 to 2 km	Most of the achievable reduction in flocks infected	Net saving in birds destroyed	Falls; almost all from infected flocks

Radius band	Epidemiological effect	Poultry cost	Human exposure
2 to 4 km	Small further reduction	Rising cost per infection averted	Falls; uninfected share growing
Above 4 km	Marginal further reduction	Tens of thousands of birds per infection averted	Falls under a low hazard weight; may not under a high one

Table 7. Recommendations.

Recommendation	Addresses	Cost	Evidence here
Adopt a small ring as the default	The band where both poultry and exposure fall	Operational	Sections 3.1, 3.2
State birds destroyed per infection averted when setting a radius	A cost that rises steeply and is rarely quoted	One calculation	Section 3.2
Report human exposure by flock infection status	The cull becoming the dominant exposure source	Operational records	Section 3.3
State the hazard weight a policy assumes	A decisive assumption left implicit	None	Section 3.5
Study seroconversion in depopulation teams by flock status	The quantity that would resolve the question	A follow-up study	Section 3.5
Protect ring-cull teams as an occupational group in their own right	Exposure created by the control measure	Protective equipment and training	Sections 3.3, 4.3

4. Discussion

4.1 Principal findings

Four findings follow. A ring of up to 2 km reduced both flocks infected and birds destroyed relative to no ring culling, so within that band there was no trade to make. Beyond it the cost per flock infection averted rose from 761 birds at 3 km to 40,073 at 8 km while infected flocks fell only from 5.8 to 2.5. The share of depopulation-related human exposure arising from uninfected flocks rose from 16 to 70 per cent across the same range. And the exposure-minimising radius moved from 8 to 4 km across plausible values of a hazard weight that is not measured.

The general observation is that a control measure with an occupational footprint should be evaluated on that footprint as well as on its epidemiological effect, and that where the two are combined the answer depends on a parameter linking them which is rarely estimated.

4.2 Relation to existing work

Spatial transmission models of avian influenza with distance kernels are well developed and have been used to compare culling and vaccination strategies [11,12,16]. The economic costs of stamping out, including compensation and the destruction of uninfected flocks, have been analysed extensively [13,17]. Human infections associated with poultry outbreaks are consistently concentrated in those with direct poultry contact, and culling participation has been identified as a risk factor in several investigations [6-8,18].

The element we add is treating the depopulation operation as an exposure-generating activity within the same model that determines how much depopulation is required. That connection is implicit in occupational guidance for culling teams but has not, so far as we can find, been incorporated into the choice of radius itself.

4.3 Implications for policy

Table 7 sets out six recommendations. Two deserve comment.

Quote the poultry cost per infection averted whenever a radius is specified. The figure is computable from the same models used to justify the policy, it rises by more than an order of magnitude across the range of radii in current use, and it makes the marginal decision explicit rather than leaving it to a round number chosen for administrative convenience.

Treat depopulation teams as an occupational group with their own exposure profile. As the radius widens, an increasing share of the work is done on uninfected flocks by people who are not the owners and who move between holdings, which is both an infection risk to them and a potential route of mechanical spread. Their protection, training and health surveillance are part of the control programme rather than an adjunct to it.

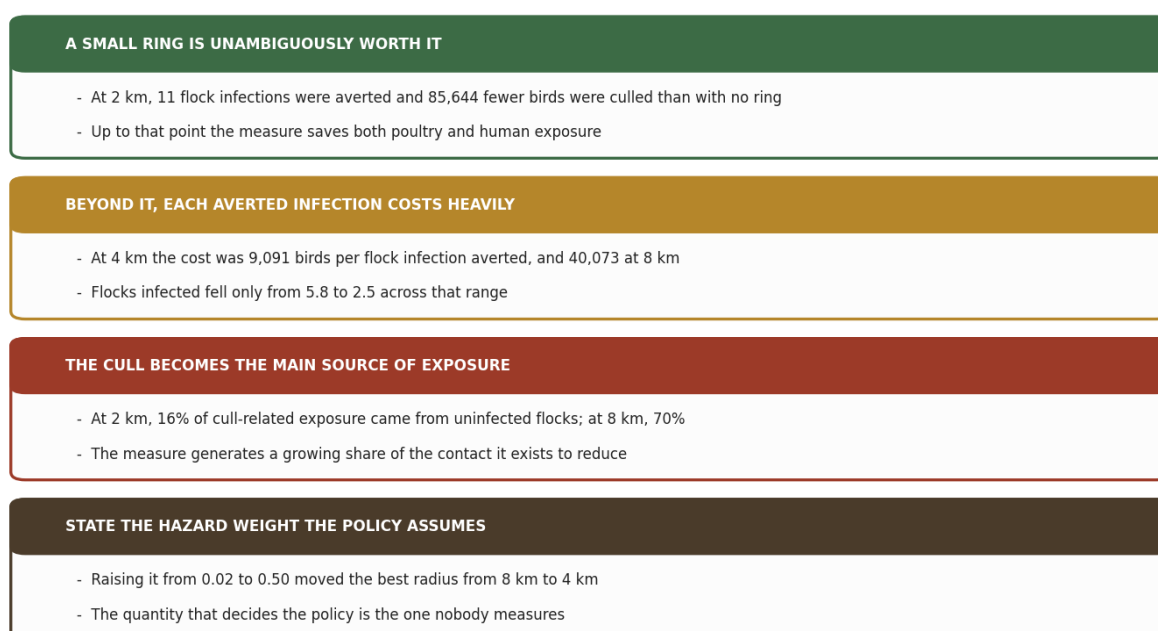


Figure 7. Proposed practice for setting and reporting a ring culling radius.

5. Limitations

The landscape is randomly distributed holdings of independent size. Real poultry production is strongly clustered, with dense areas where a 3 km ring may contain dozens of holdings and sparse areas where it contains none. Clustering would sharpen every result here, making small rings more effective and large ones far more costly in the dense areas where they are most often invoked.

We model a single homogeneous transmission kernel and no distinction between production types, biosecurity levels or airborne versus contact-mediated spread. Nor do we model movement restrictions, which operate alongside ring culling in every real scheme and which would reduce the epidemic independently of the radius.

Human exposure is proportional to birds handled with a fixed hazard weight, and the model contains no protective equipment, no variation in team practice and no dose-response. It also does not model human-to-human transmission, which is the outcome that makes these viruses a pandemic concern rather than an occupational one; a policy chosen to minimise total exposure is not necessarily the policy that minimises the probability of an adapted virus emerging.

The ordinary husbandry term assumes that contact continues unchanged on uninfected uncontrolled farms during an outbreak, whereas in practice heightened biosecurity reduces it. This makes long epidemics look worse than they are and therefore favours wider rings; correcting it would shift the optimum inward.

Finally, we do not model compensation, the willingness of producers to report suspicion when a wide ring is in force, or the consequence of delayed reporting. A radius wide enough to destroy a producer's neighbours may lengthen the detection delay that the whole scheme depends on, which is a feedback that would work against the wider rings our base case favours.

6. Conclusion

In simulated poultry landscapes, a ring culling radius of up to 2 km reduced flocks infected from 17.0 to 5.8 while destroying 85,644 fewer birds than no ring culling at all. Within that band the measure costs nothing in poultry and reduces human exposure, and the case for it is unambiguous.

Wider rings bought little further epidemiological benefit at steeply rising cost: from 761 birds per flock infection averted at 3 km to 40,073 at 8 km, with flocks infected falling only from 5.8 to 2.5. Across the same range the share of depopulation exposure generated by uninfected

flocks rose from 16 to 70 per cent, so the control measure became the main occasion of human contact with poultry.

Whether that shift matters depends on how hazardous depopulating an uninfected flock is relative to an infected one. Moving that assumption across its plausible range moved the exposure-minimising radius from 8 to 4 km. The quantity is not currently measured, and serological follow-up of depopulation teams stratified by flock infection status would settle it.

Declarations

Ethics approval and consent to participate. Not applicable. This study used entirely synthetic data generated by the authors. No animals, human participants, holdings, tissue or records were involved, and no outbreak or surveillance data were accessed. Institutional review board, ethics committee and animal ethics approval were therefore not required.

Consent for publication. Not applicable.

Data availability statement. No real-world data were used. All results were generated by the simulation script described in Section 2, provided as supplementary material with all random seeds and every parameter stated in full in Table 1. Every figure and every value in Tables 2 to 5 can be regenerated exactly by executing it. The script will be deposited in a public repository with a permanent identifier on acceptance.

Conflict of interest. The authors declare that they have no competing interests, financial or non-financial, in relation to the subject matter of this manuscript. No author has any financial or advisory relationship with any poultry production business, vaccine manufacturer or provider of depopulation services.

Funding. This research received no specific grant from any funding agency in the public, commercial or not-for-profit sectors.

Authors' contributions. [AO] conceived the study, designed the model and drafted the manuscript. [AT] implemented the simulation, performed the analysis and verified all reported values. [ATh] contributed the poultry production and depopulation operations framing and the recommendations. All authors critically revised the manuscript, approved the final version, and agree to be accountable for all aspects of the work.

Acknowledgements. None declared.

Use of artificial intelligence. The authors should disclose here any use of AI-assisted tools in manuscript preparation, in accordance with the journal's policy.

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