

ORIGINAL RESEARCH

The Indicator That Moves and the People Who Do Not Benefit: Livestock Antimicrobial Use Reduction, Attribution and Response Lag

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Abstract

Background. National programmes reduce antimicrobial use in food animals and report success through resistance prevalence in livestock. The human benefit depends on two quantities that indicator does not carry: the share of human resistance originating in the animal reservoir, and the time the human reservoir takes to respond.

Methods. We built a coupled two-reservoir model of resistant colonisation in livestock and humans, with selection proportional to antimicrobial use in each and bidirectional transmission between them. A farm-worker subgroup was given a fourfold higher animal exposure. We computed equilibrium prevalence, the animal-attributable fraction by counterfactual, and 25-year trajectories following a reduction in livestock use.

Results. At baseline, resistance prevalence was 47.4 per cent in livestock, 57.2 per cent in the general population and 68.2 per cent in farm workers, with an animal-attributable fraction of 12.6 per cent. A 60 per cent reduction in livestock use lowered livestock resistance by 87.9 per cent, farm-worker resistance by 20.5 per cent and general population resistance by 10.7 per cent, so the animal indicator overstated the general human benefit 8.2-fold. Across attributable fractions from 3.8 to 20.4 per cent the livestock fall was near-constant at about 88 per cent while the human fall ranged from 3.3 to 16.5 per cent. Three years after the reduction the livestock response was 76 per cent complete against a long-run 88 per cent, while the human response had reached 73 per cent of its eventual value. Reducing use in both reservoirs gave a 45.8 per cent fall in human resistance against 31.6 per cent for the sum of each acting alone.

Conclusion. Livestock resistance prevalence is a poor proxy for human benefit. Attribution should be estimated before a programme is designed, evaluation windows should allow for lag, and the two reservoirs should be addressed together.

Keywords: antimicrobial resistance; veterinary public health; agricultural occupational health; One Health interface; livestock health; attributable fraction.

1. Introduction

Antimicrobial use in food animals exceeds human clinical use by weight in many countries, and reducing it has become a central plank of national action plans on antimicrobial resistance [1-3]. Several countries have achieved reductions of more than half in veterinary sales within a decade, accompanied by clear falls in resistance among livestock isolates [4-6].

Whether those falls have delivered a corresponding benefit to human health is much less clear, and the evidence is mixed across organisms and settings [7-9]. Part of the difficulty is that the quantity routinely monitored and reported is resistance prevalence in animals, which is the intermediate outcome, while the outcome of interest is resistance in people.

Two quantities stand between them. The first is the animal-attributable fraction: the share of human resistance that originates in the animal reservoir rather than being selected and maintained by clinical use in humans. That fraction varies greatly by organism and resistance determinant, from substantial for some zoonotic enteric bacteria to very small for organisms that circulate almost entirely in healthcare settings [10-12].

The second is time. The human reservoir has its own dynamics, with resistant colonisation maintained by human antimicrobial use and lost slowly, so a change in the animal input propagates with a delay set by human, not animal, turnover.

Neither quantity is visible in an animal-side surveillance figure, and both determine what a programme achieves. We therefore modelled the two reservoirs explicitly and asked what a livestock use reduction delivers, to which population, and over what period.

1.1 Objectives

We aimed to quantify the long-run effect of livestock antimicrobial use reduction on resistance in livestock, in farm workers and in the general population; to establish how far the animal indicator overstates the human benefit; to determine the sensitivity of the human effect to the attributable fraction; to characterise the response lag; and to compare livestock and clinical stewardship as levers, including their interaction.

2. Materials and Methods

2.1 Model

We represent resistance as the prevalence of resistant colonisation in two reservoirs, livestock and humans, each between zero and one. In each reservoir, resistant colonisation spreads at a rate proportional to antimicrobial use, is lost at a constant rate reflecting fitness cost and population turnover, and is acquired from the other reservoir in proportion to that reservoir's prevalence:

$$dA/dt = s_a u_a A(1-A) - \mu_a A + \varphi_{ha} H(1-A) \quad (1)$$

$$dH/dt = s_h u_h H(1-H) - \mu_h H + \varphi_{ah} A(1-H) \quad (2)$$

The cross-reservoir terms represent transmission through food, direct contact and the environment. The animal-to-human term is the larger of the two, reflecting the dominant direction of flow, and it is the parameter that determines attribution.

A farm-worker subgroup follows the same human dynamics with the animal-to-human term multiplied by 4, representing sustained occupational contact with livestock and their environment. The subgroup does not feed back into the main reservoirs, which understates its role as a bridge population and is discussed in Section 5.

The animal-attributable fraction is computed by counterfactual: the proportional reduction in equilibrium human prevalence when the animal-to-human term is set to zero, holding all else constant.

Equations were integrated with weekly steps. Each scenario starts from the baseline equilibrium and applies the new use levels for 25 years. Parameters are given in Table 1; all are illustrative and are not calibrated to any organism or country.

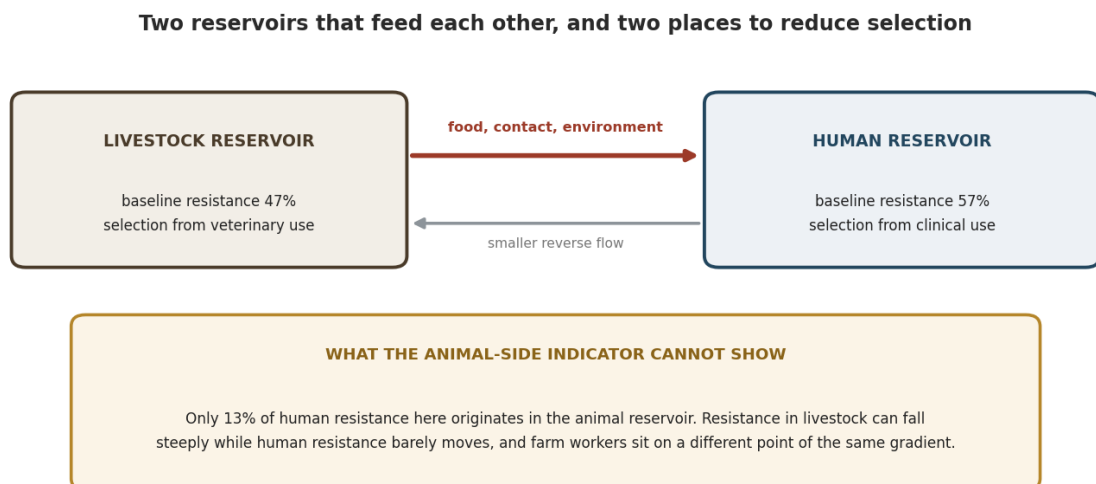


Figure 1. The two-reservoir structure and what the animal-side indicator does not show.

Table 1. Model parameters.

Parameter	Value	Interpretation
Selection, animals	2.6 per unit use per year	Rate at which use spreads resistant colonisation
Selection, humans	2.2 per unit use per year	As above, in the human reservoir
Loss, animals	1.4 per year	Fitness cost plus herd turnover
Loss, humans	1.1 per year	Fitness cost plus clearance
Animal to human transmission	0.45 per year	Food, contact and environmental routes
Human to animal transmission	0.05 per year	Smaller reverse flow
Occupational multiplier	4×	Applied to the animal-to-human term for farm workers
Horizon	25 years	Long enough for both reservoirs to equilibrate

3. Results

3.1 Baseline and attribution

At the baseline equilibrium, resistant colonisation prevalence was 47.4 per cent in livestock, 57.2 per cent in the general human population and 68.2 per cent among farm workers.

Setting the animal-to-human term to zero reduced equilibrium human prevalence by 12.6 per cent, which is the animal-attributable fraction in this parameterisation. The remaining 87.4 per cent is maintained by human antimicrobial use and human-to-human transmission and is untouchable by any veterinary intervention.

That figure is the ceiling on what livestock action can achieve for the general population, and it is a property of the system rather than of the programme. Everything below is bounded by it.

3.2 Three populations, three responses

Table 2 and Figure 2 give the long-run effect of reducing livestock antimicrobial use. Livestock resistance responds steeply: a 40 per cent reduction in use lowered it by 62.0 per cent and a 60 per cent reduction by 87.9 per cent.

Farm-worker resistance responded less, falling 20.5 per cent at a 60 per cent use reduction, and general population resistance least, falling 10.7 per cent. Complete elimination of livestock use lowered general population resistance by 12.0 per cent, close to the attributable fraction as expected.

The ordering is the substantive result. The intervention acts directly on the livestock reservoir, reaches farm workers strongly because their exposure to that reservoir is high, and reaches the general population weakly because most of their resistance has a different origin.

This means livestock antimicrobial stewardship is, among other things, an agricultural occupational health measure. The population that benefits most in proportional terms is the one working with the animals, and that benefit is roughly double the general-population benefit throughout the range.

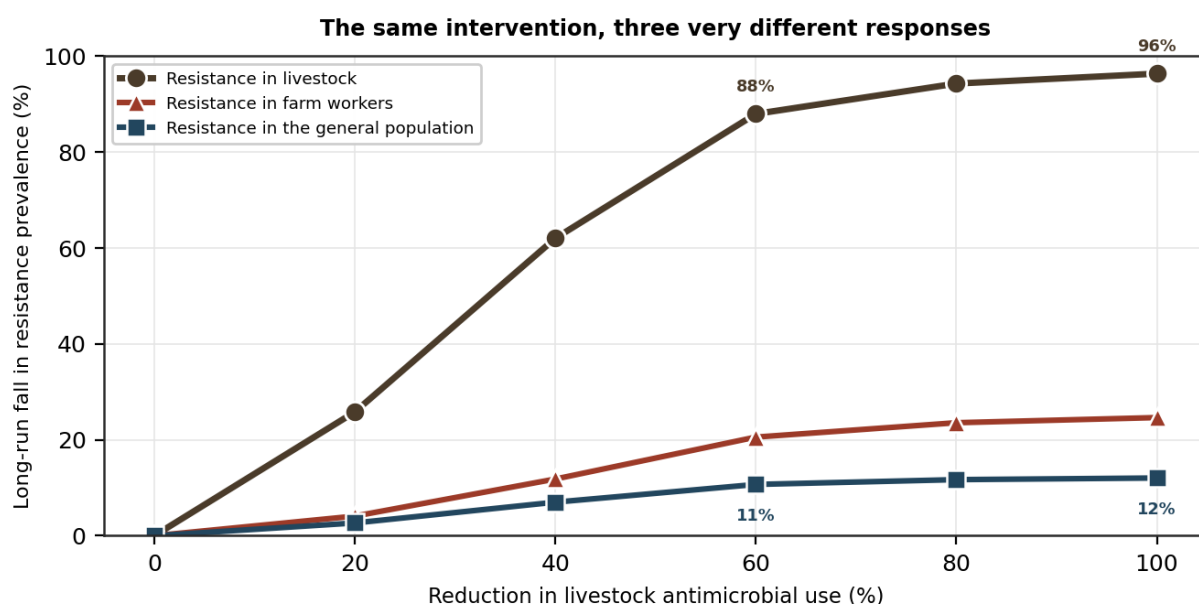


Figure 2. Long-run fall in resistance in each population against livestock use reduction.

Table 2. Long-run effect of reducing livestock antimicrobial use.

Use reduction	Livestock resistance (%)	Livestock fall (%)	Farm-worker fall (%)	General population resistance (%)	General population fall (%)
0%	47.4	0.0	0.0	57.2	0.0
20%	35.2	25.8	4.1	55.7	2.7
40%	18.0	62.0	11.8	53.2	7.0
60%	5.7	87.9	20.5	51.1	10.7
80%	2.7	94.2	23.5	50.5	11.7
100%	1.8	96.3	24.6	50.4	12.0

3.3 The indicator overstates the benefit

Table 3 and Figure 3 express the mismatch directly. At every level of reduction the proportional fall in livestock resistance exceeded the fall in general population resistance by a factor between 8.0 and 9.7.

At the 60 per cent reduction typical of successful national programmes, the ratio was 8.2: livestock resistance fell 87.9 per cent while general population resistance fell 10.7 per cent.

The stability of the ratio across the range is worth noting, because it means the discrepancy is not a threshold effect that disappears at high reduction. It is a structural feature of a system in

which most human resistance has a non-animal origin, and it would be present in any monitoring scheme that reports the animal figure as the outcome.

We would not describe the animal indicator as wrong. It accurately measures what it measures, and it is the correct indicator for the veterinary objective of reducing resistance in livestock, which has its own animal health and production value. The difficulty arises when it is presented as evidence of human benefit, because the two move by very different amounts.

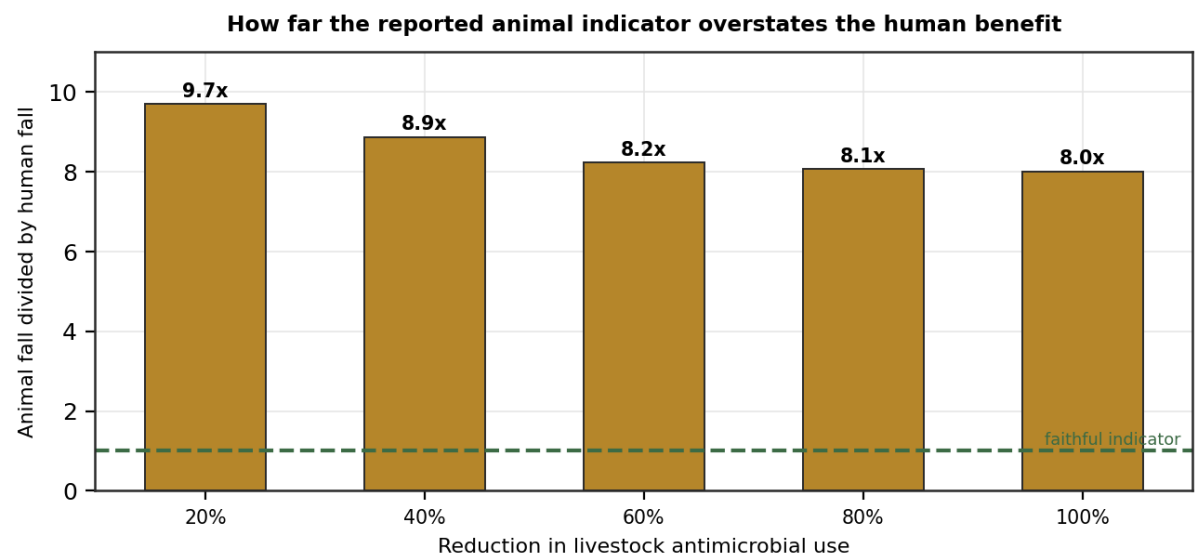


Figure 3. Ratio of the proportional fall in livestock resistance to that in general population resistance.

Table 3. The indicator gap.

Livestock use reduction	Fall in livestock resistance	Fall in general population resistance	Ratio
20%	25.8%	2.7%	9.7×
40%	62.0%	7.0%	8.9×
60%	87.9%	10.7%	8.2×
80%	94.2%	11.7%	8.1×
100%	96.3%	12.0%	8.0×

3.4 Attribution sets the human effect

Table 4 and Figure 4 vary the strength of the animal-to-human pathway, giving attributable fractions from 3.8 to 20.4 per cent.

Across that entire range the livestock response to a 60 per cent use cut was essentially unchanged, from 88.0 to 87.7 per cent. The general human response varied more than fivefold, from 3.3 to 16.5 per cent.

The animal indicator therefore carries no information whatever about the quantity that determines the human benefit. Two countries running identical programmes on organisms with

different attributable fractions would report near-identical animal-side successes and obtain human results differing by a factor of five.

This argues for estimating attribution before designing a programme rather than after evaluating one. Source attribution methods based on genomic comparison, exposure modelling or outbreak investigation exist and are imperfect, but an imprecise estimate of a decisive quantity is more useful than a precise measurement of an indicator that does not bear on it.

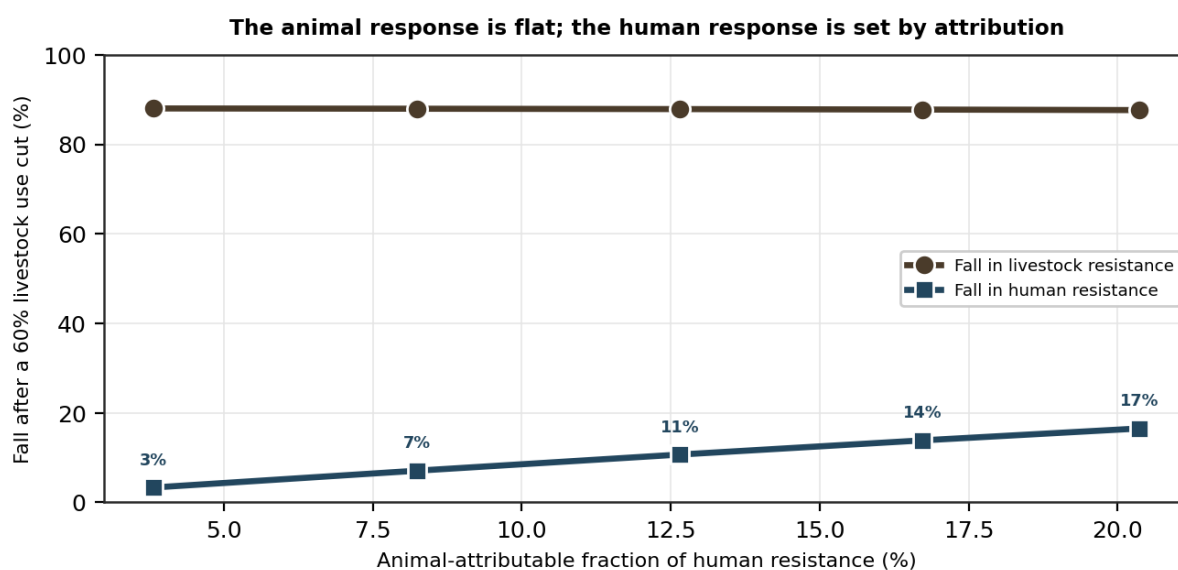


Figure 4. Response to a 60 per cent livestock use cut across attributable fractions.

Table 4. Effect of the attributable fraction on the outcome of a 60 per cent livestock use cut.

Pathway strength	Attributable fraction	Baseline human resistance (%)	Fall in livestock resistance	Fall in human resistance
0.10	3.8%	52.0	88.0%	3.3%
0.25	8.2%	54.5	88.0%	7.1%
0.45	12.6%	57.2	87.9%	10.7%
0.70	16.7%	60.0	87.8%	13.9%
1.00	20.4%	62.8	87.7%	16.5%

3.5 The human reservoir lags

Table 5 and Figure 5 follow the 25-year trajectory after a 60 per cent livestock use reduction. The livestock reservoir responds quickly: 48.4 per cent of its eventual fall was achieved within one year and 76.2 per cent within three.

The human reservoir lags. At one year the general population fall was 2.8 per cent, which is 26 per cent of its long-run value; at three years 7.8 per cent, or 73 per cent; and 99 per cent of the eventual benefit had accrued only by year 10.

The evaluation implication is direct. A programme assessed at three years, which is a common cycle for national action plans, would observe a large and unambiguous animal-side success alongside a small human change that is within the noise of most surveillance systems. The natural conclusion — that the livestock intervention did not help people — would be wrong, but it would be wrong in a way the data at that point cannot distinguish from correct.

The lag arises because the human reservoir is maintained largely by its own dynamics. Removing part of its input changes its equilibrium, but the approach to that equilibrium is governed by the rate at which resistant colonisation is lost from humans, not by how fast the animal reservoir changed.

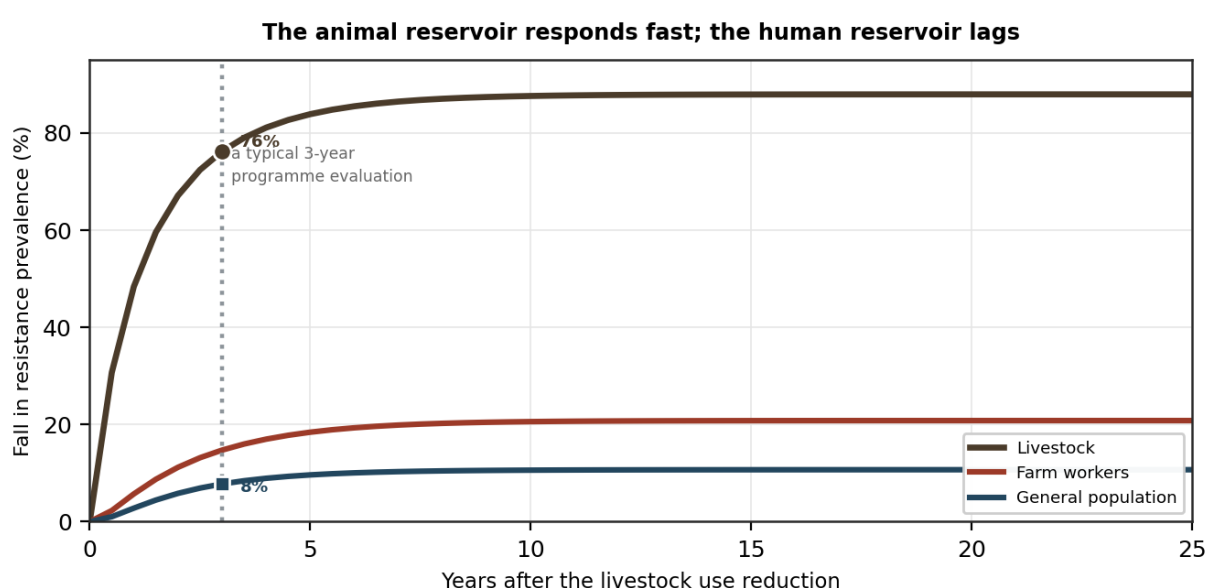


Figure 5. Trajectory of resistance in each population after a 60 per cent livestock use reduction.

Table 5. Time course following a 60 per cent livestock use reduction.

Year	Livestock fall	Farm-worker fall	General population fall	Share of long-run human benefit
1	48.4%	5.7%	2.8%	26.1%
2	67.1%	11.2%	5.8%	54.5%
3	76.2%	14.7%	7.8%	72.6%
5	83.8%	18.4%	9.6%	90.1%
10	87.5%	20.6%	10.6%	99.2%
15	87.9%	20.8%	10.7%	99.9%
20	87.9%	20.8%	10.7%	100.0%
25	87.9%	20.8%	10.7%	100.0%

3.6 Two levers and their interaction

Table 6 and Figure 6 compare livestock and clinical stewardship. A 60 per cent livestock use reduction lowered general population resistance by 10.7 per cent and farm-worker resistance

by 20.5 per cent. A 30 per cent reduction in human clinical use did the reverse, lowering general population resistance by 21.0 per cent and farm-worker resistance by 8.7 per cent.

Applying both lowered general population resistance by 45.8 per cent, against 31.6 per cent for the sum of the two acting separately. The combination therefore delivered more than the sum of its parts.

The superadditivity has a clear mechanism. Each reservoir seeds the other, so reducing selection in one lowers the input to the other and thereby lowers the reservoir that was seeding it back. Acting on both interrupts the loop rather than trimming each arm of it independently. The practical reading is that presenting agricultural and clinical stewardship as competing claims on a single budget understates what a coordinated programme would achieve.

The distributional point from Section 3.2 also recurs here in sharper form. Livestock action delivered roughly twice as much to farm workers as to the general population; clinical stewardship delivered roughly twice as much to the general population as to farm workers. The two levers are not merely complementary in magnitude but in whom they protect.

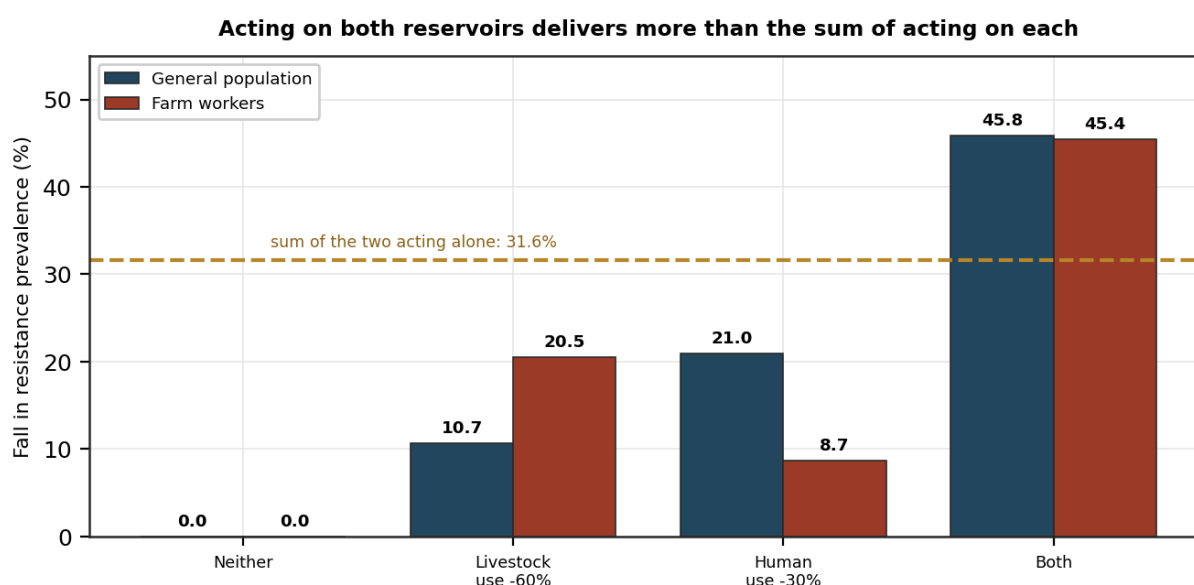


Figure 6. Effect of livestock and clinical stewardship separately and together.

Table 6. Comparison of the two levers.

Scenario	Livestock resistance (%)	General population fall	Farm-worker fall	Livestock fall
Neither	47.4	0.0%	0.0%	0.0%
Livestock use -60%	5.7	10.7%	20.5%	87.9%
Human use -30%	47.1	21.0%	8.7%	0.5%
Both	3.7	45.8%	45.4%	92.1%

Sum of the two levers acting alone: 31.6% for the general population. Acting together: 45.8%.

Table 7. Recommendations.

Recommendation	Addresses	Cost	Evidence here
Estimate the attributable fraction before designing a programme	A decisive quantity the animal indicator omits	Source attribution study	Section 3.4
Do not report livestock resistance as the human outcome	An indicator that overstates benefit severalfold	Reporting change	Section 3.3
Set evaluation windows of a decade, not three years	A lag that reads as programme failure	Longer commitment	Section 3.5
Report resistance in occupationally exposed groups separately	Benefit concentrated in a group not separately counted	Surveillance stratification	Section 3.2
Fund agricultural and clinical stewardship together	Superadditive levers treated as alternatives	Coordination	Section 3.6
State which population a programme is intended to protect	Distributional choice made implicitly	None	Sections 3.2, 3.6

4. Discussion

4.1 Principal findings

Four findings follow. A 60 per cent livestock use reduction lowered livestock resistance 88 per cent and general population resistance 10.7 per cent, so the reported animal indicator overstated the human benefit 8.2-fold. The human effect was governed by the attributable fraction, varying more than fivefold across plausible values while the animal effect was unchanged. The human response lagged, reaching 73 per cent of its eventual value at three years against a livestock response 76 per cent complete. And the two stewardship levers were superadditive, giving 45.8 per cent against 31.6 per cent for the sum of each alone.

Taken together these say that the standard monitoring arrangement for these programmes reports the fastest-moving and least relevant quantity on the shortest timescale, and that the resulting picture is systematically misleading in both directions — overstating benefit in cross-section and understating it over time.

4.2 Relation to existing work

Reductions in veterinary antimicrobial sales and accompanying falls in livestock resistance are well documented in several national programmes [4-6,13]. The human consequences have been harder to establish and the literature reports mixed findings across organisms [7-9,14]. Source attribution for resistant organisms is an active field using genomic, epidemiological and modelling approaches, with estimates varying widely by determinant [10-12,15]. Coupled-reservoir models of resistance transmission between animal and human populations have been developed and used to examine intervention scenarios [16-18].

Our contribution is to bring the indicator problem, the attribution dependence and the response lag into a single framework and to attach numbers to each, including the distributional result that farm workers and the general population experience very different benefits from the same intervention. That last point seems to us underemphasised given that occupational exposure is the clearest and most direct animal-to-human pathway.

4.3 Implications

Table 7 sets out six recommendations. Two deserve comment.

Match the evaluation window to the reservoir being evaluated. The animal-side objective can be assessed within a few years; the human-side objective cannot. Committing to a decade-long evaluation is a political difficulty rather than a technical one, but reporting a three-year human result as though it were the final answer is a technical error and a predictable one.

Count the occupationally exposed separately. Farm workers, abattoir staff and veterinarians are the population for whom the animal reservoir is the dominant source, and they are the clearest beneficiaries of veterinary stewardship. Most national resistance surveillance does not identify them, so the benefit that is largest and arrives earliest is also the one least likely to be measured.

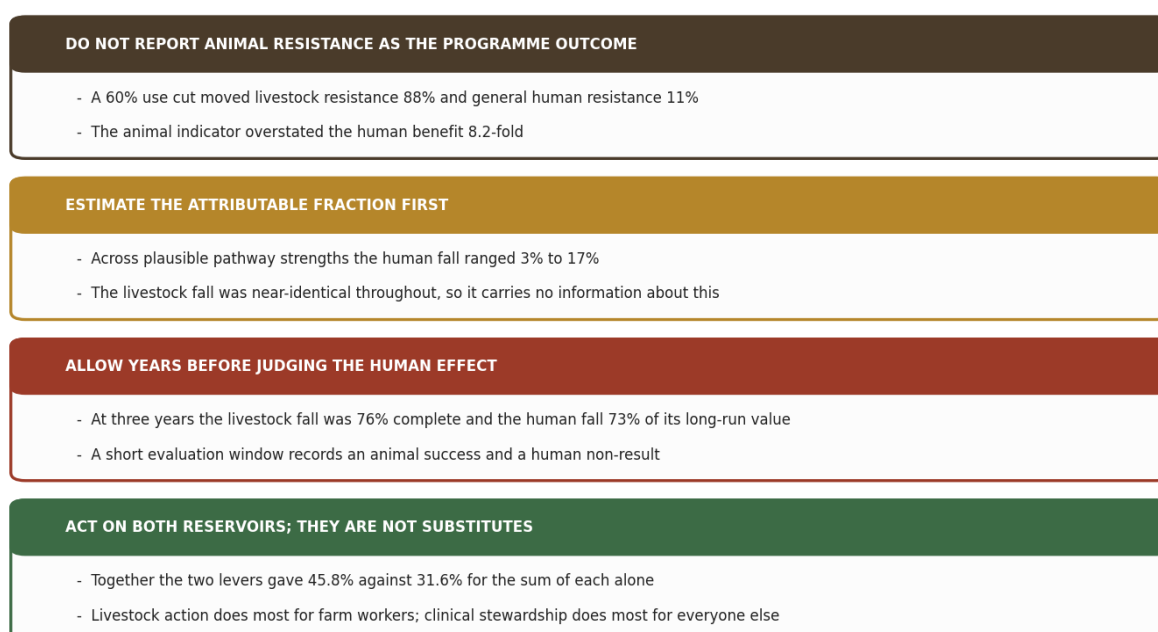


Figure 7. Proposed practice for designing and evaluating livestock antimicrobial stewardship programmes.

5. Limitations

This is a compartmental model of colonisation prevalence with no organism, no resistance determinant and no country. It cannot produce estimates for any real programme, and the parameter values were chosen to give a plausible endemic situation rather than fitted to data. The numbers should be read as illustrating relationships, not as predictions.

We model a single resistance phenotype in a single bacterial population. Real resistance is carried on mobile genetic elements that move between species, so selection by one agent in one host can maintain resistance to another agent in a different host, and co-selection can decouple resistance prevalence from the use of the corresponding drug entirely. That mechanism would weaken the response to any single-agent reduction and is absent here.

The farm-worker subgroup does not feed back into either main reservoir. In reality occupationally exposed people are a bridge population, carrying resistance from the animal reservoir into households and healthcare settings, which would raise the attributable fraction for the general population above what we compute and make the occupational group more important than our results suggest.

Transmission terms are constant and there is no environmental compartment, no international trade in animals or food, and no travel. Environmental reservoirs in particular have their own long persistence and would add a further lag beyond the one we report.

Finally, we treat antimicrobial use as a single scalar in each reservoir. Real reductions are not uniform across agents, and a programme that removes use of agents unimportant to human medicine while leaving critically important ones in place will have a smaller human effect than the same headline reduction applied to the agents that matter. Our model cannot distinguish the two.

6. Conclusion

In a coupled two-reservoir model, a 60 per cent reduction in livestock antimicrobial use lowered resistance in livestock by 88 per cent, in farm workers by 21 per cent and in the general population by 11 per cent. The animal-side indicator that such programmes report overstated the general human benefit by a factor of 8.2, consistently across the whole range of reductions.

The size of the human benefit was determined by the animal-attributable fraction, which the animal indicator does not reflect at all: across attributable fractions from 4 to 20 per cent the

livestock response was unchanged while the human response varied more than fivefold. The human response also lagged, reaching 73 per cent of its eventual value at three years.

Reducing use in both reservoirs delivered 45.8 per cent against 31.6 per cent for the two acting separately, because each reservoir seeds the other. Livestock stewardship is worth doing, is worth doing for farm workers most of all, and should be reported against the population it is meant to protect and over the period in which that population can respond.

Declarations

Ethics approval and consent to participate. Not applicable. This study used entirely synthetic data generated by the authors. No animals, human participants, tissue, isolates or records were involved, and no 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 model script described in Section 2, provided as supplementary material with every parameter stated in full in Table 1. Every figure and every value in Tables 2 to 6 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 manufacturer of veterinary or human antimicrobials, or with any livestock production or food processing business.

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Authors' contributions. [AO] conceived the study, formulated the model and drafted the manuscript. [AT] implemented the model, performed the analysis and verified all reported values. [ATh] contributed the veterinary stewardship and surveillance 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.

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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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